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Summer 2000 Student/Faculty Science Campaign, July 31-August 8, 2000

Arnold L. Snyder, Jr., Editor

NorthWest Research Associates, Inc.
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14. ABSTRACT
The primary objective of the Summer 2000 Student / Faculty Science Campaign was to provide competitively selected university faculty and students with opportunities for upper atmospheric and space physics research involving the HAARP high frequency transmitter and associated diagnostic instrumentation located near Gakona, Alaska. This report documents the technical program and participants and includes a compilation of the Student / Faculty experiment summaries in areas ionospheric generation of ULF/ELF/VLF radiowaves, D-Region diagnostics, SuperDARN observations of HAARP induced ionospheric irregularities, and potential for telescopic assessments of HAARP induced ionospheric airglow.

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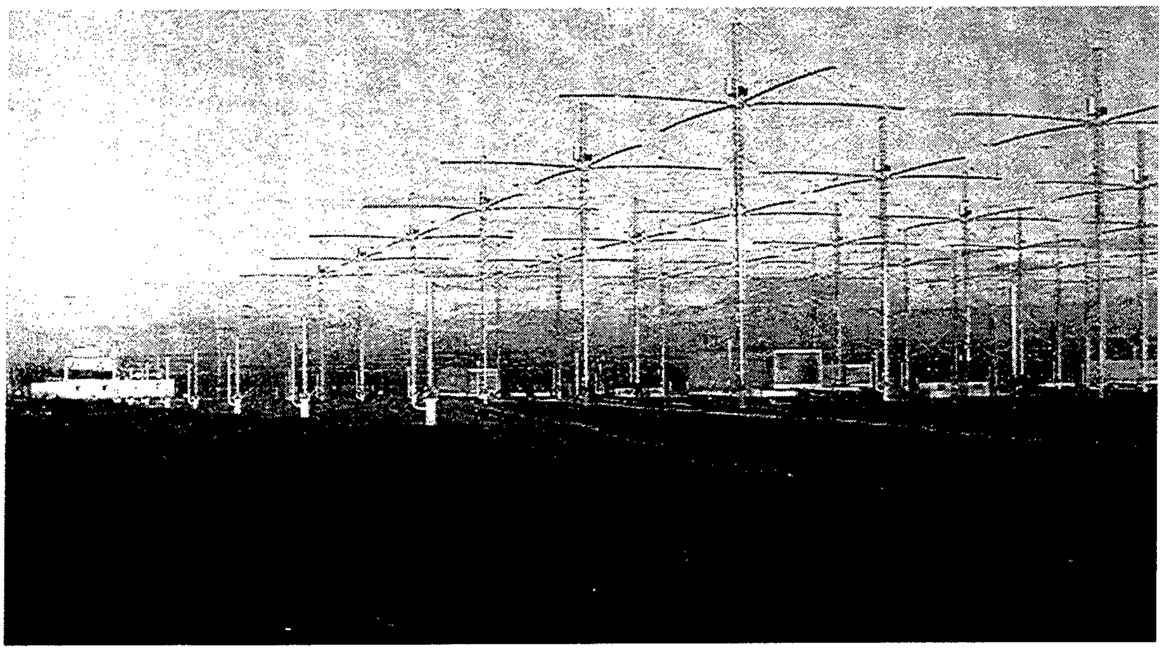

High Frequency Active Auroral Research Program (HAARP) Research Station, Gakona, AK, site of the experimentation phase of the Summer 2000 Student / Faculty Science Campaign. The 960 kW, 2.8 – 8.4 MHz, HAARP transmit antenna array is shown prominently in the photograph.

Summer 2000 Student / Faculty Science Campaign

Objective

The primary objective was to provide competitively selected university faculty and students with opportunities for upper atmospheric and space physics research involving the HAARP high frequency transmitter and associated diagnostic instrumentation located near Gakona, Alaska. The nine-day program also acquainted the faculty and students with other Alaskan facilities that may contribute to specific research programs.

NorthWest Research Associates was responsible for publishing the Science Campaign results as well as for organizing and coordinating the Summer School in cooperation with the University of Alaska Fairbanks.

Approach

A university faculty member and associated student(s) prepared proposals to demonstrate some aspect of upper atmospheric or space physics using the HAARP high frequency transmitter and associated diagnostic instrumentation. These proposals were submitted to the HAARP Program Office for evaluation and potential selection.

A committee comprised of scientists from the Air Force Research Laboratory and the Naval Research Laboratory selected the proposals for support. The winning proposals were selected on the basis of technical quality and association to the student's interests and field of study. Following selection, each student / faculty team prepared and submitted a brief summary of their demonstration which was distributed at the April 2000 Santa Fe Ionospheric Interactions Workshop. The faculty member of each team prepared a tutorial lecture for presentation as part of the summer program.

The technical program began at the University of Alaska Fairbanks and concluded with campaign experiments and demonstrations at HAARP's Gakona, Alaska field site. Four days were spent at the University with tutorial sessions and discussions of atmospheric and space physics including overview of diagnostic techniques. Visits to the Poker Flat Research Range and HIPAS acquainted the faculty and students with other Alaskan Research facilities.

Travel to the HAARP area was by van and included a wildlife tour of McKinley National Park and opportunities to enjoy the "Alaskan Experience."

At HAARP there was an orientation program that described and demonstrated the facility capabilities. The three days spent at HAARP included presentation of the faculty tutorials, the experiments and demonstrations, student summaries of results, and a concluding talk "Frontiers of Radio Science presented by invited speaker Professor Robert Hunsucker, Editor of the *Radio Science* journal.

This report documents the technical program, the participants and includes a compilation of the Student / Faculty experiment summaries.

Summer 2000 Student / Faculty Science Campaign
Technical Program

July 31

6:30 PM	Icebreaker / Dinner	

August 1

8:00 AM	Welcome	Chancellor Marshall Lind, UAF Professor Syun-Ichi Akasofu, IARC - UAF Professor Roger Smith, GI – UAF Dr. Paul Kossey, AFRL
8:30 AM	Program Overview	Dr. Paul Kossey, AFRL
9:00 AM	Polar Thermosphere and Mesosphere	Professor Michael Kelley, Cornell
10:45 AM	Polar Ionosphere	Dr. Robert Robinson, NSF
1:30 PM	Geophysical Institute	Professor Roger Smith, GI – UAF
2:30 PM	Tour Geophysical Institute	Professor Roger Smith, GI – UAF

August 2

8:00 AM	The Aurora	Professor Syun-Ichi Akasofu, IARC – UAF
9:00 AM	Sub-Auroral Ionosphere	Dr. John Foster, Haystack - MIT
10:15 AM	Radiowave Interactions in the Ionosphere	Professor Alfred Wong, UCLA
11:15 AM	HAARP Diagnostic Instruments	John Rasmussen, NWRA
11:55 AM	Lidar and Lidar Facilities	Professor Richard Collins, UAF
2:00 PM	HIPAS Overview and Tour	Professor Alfred Wong, UCLA
3:00 PM	HIPAS Lidar	Professor Ralph Wuerker, UCLA

Summer 2000 Student / Faculty Science Campaign

Technical Program

August 3

8:00 AM	Optical Instruments	Professor Roger Smith, GI – UAF
9:00 AM	SuperDARN Overview	Professor William Bristow, GI - UAF
10:15 AM	Incoherent Scatter Radar Theory	Professor William Bristow, GI – UAF
11:15 AM	Incoherent Scatter Radar Practice	Dr. John Foster, Haystack – MIT
1:15 PM	*Radio Science* Journal	Professor Robert Hunsucker, AGU
2:45 PM	Poker Flat Research Range Tour	Dr. Greg Walker, PFRR – UAF

August 4

8:00 AM	ELF Program	Professor Davis Sentman, GI – UAF
9:00 AM	Magnetometer Networks and ULF Waves	Professor John Olson, GI - UAF
10:30 AM	Planning HAARP Experiments	Edward Kennedy, NRL
11:30 AM	Experiment Tutorial	Professor James Sheerin,
1:30 PM	Experiment Tutorials	Professor John Olson, GI – UAF Professor Timothy Bell[1], Stanford Dr. Keith Groves, AFRL
4:30 PM	Travel to Healy, AK	"The Alaskan Experience"

August 5

6:30 AM	Travel to Glennallen, AK	"The Alaskan Experience"

[1] Professor Umran Inan (Stanford) presented Professor Bell's tutorial.

Summer 2000 Student / Faculty Science Campaign

Technical Program

August 6

9:00 AM	HAARP Overview	Dr. Paul Kossey, AFRL
9:30 AM	HAARP Facility Tour	Edward Kennedy, NRL
1:00 PM	Faculty Tutorials	Professor Min-Chang Lee, MIT Professor Spencer Kuo, Polytechnic Univ. Professor Umran Inan, Stanford
3:30 PM	Student / Faculty Experiments	

August 7

9:00 AM	Experiment Summaries	Jonathan Mills, Eastern Michigan Kim Falinski, MIT Keith Carney, UAF Robert Moore, Stanford
10:00 AM	Telescopic Airglow Measurements	Elizabeth Gerken, Stanford
10:30 AM	Student / Faculty Experiments	
2:15 PM	Polar Mesospheric Summer Echoes and Noctilucent Clouds	Dr. Mercedes Huaman, Cornell
2:45 PM	Graduate Student Experiences at HIPAS / HAARP	Jacquline Pau, UCLA

August 8

9:00 AM	Experiment Summaries	Ryan Riddolls, MIT Piotr Jastrzebski, MIT Camilo Ramos, Cornell Daniel Bivolaru, Polytechnic Univ.
10:00 AM	HAARP S/W Development	Tyler Wellman, Brown Univ.
10:15 AM	Frontiers in Radio Science Invited Presentation	Professor Robert Hunsucker, OIT / AGU
10:45 AM	Program Wrap-up	Dr. Paul Kossey, AFRL

Participants

Summer 2000 Student / Faculty Science Campaign

Sponsored by
High Frequency Active Auroral Research Program (HAARP)
Organized and Coordinated by
Northwest Research Associates, Inc.

Student / Faculty Teams

Air Force Research Laboratory
- Kim Falinski (MIT)
- Tyler Wellman (Brown University)
- Dr. Keith Groves

Cornell University
- Mercedes Huaman
- Camilo Ramos
- Professor Michael Kelley

Eastern Michigan University
- Jonathan Mills
- Professor James Sheerin

Massachusetts Institute of Technology
- Piotr Jastrzebski
- Ryan Riddolls
- Professor Min-Chang Lee

Polytechnic University
- Daniel Bivolaru
- Professor Spencer Kuo

Stanford University
- Robert Moore
- Professor Timothy Bell

Stanford University
- Elizabeth Gerken
- Professor Umran Inan

University of Alaska Fairbanks
- Justin Northrop
- Professor William Bristow

University of Alaska Fairbanks
- Keith Carney
- Professor John Olson

University of Alaska Fairbanks
- Fernanda Tavares
- Professor Davis Sentman

University of California at Los Angeles
- Jacqueline Pau
- Professor Alfred Wong

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Professor Subhash Antani
Edgewood College

Professor Richard Collins
University of Alaska Fairbanks

Dr. John Foster
Haystack Observatory, Massachusetts Institute of Technology

Professor Robert Hunsucker – invited speaker
Oregon Institute of Technology
Editor of *Radio Science*

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Advanced Power Technologies, Inc.

Dr. Robert Robinson
National Science Foundation

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University of Alaska Fairbanks

Professor Ralph Wuerker
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Lee Snyder
NorthWest Research Associates

HAARP VLF D-Region Diagnostics
Summer 2000

Timothy F. Bell
Robert C. Moore
STAR Laboratory, Stanford University
Stanford. CA 94305

Abstract:

The HAARP VLF D-region diagnostics system is designed to determine the altitude profile of the collision frequency in the ionospheric D-region heated by the HAARP HF transmitter. This determination requires the measurement at three ground sites of the HAARP-induced phase and amplitude changes of three subionospheric narrowband VLF signals that propagate under the heated region (Figure 1).

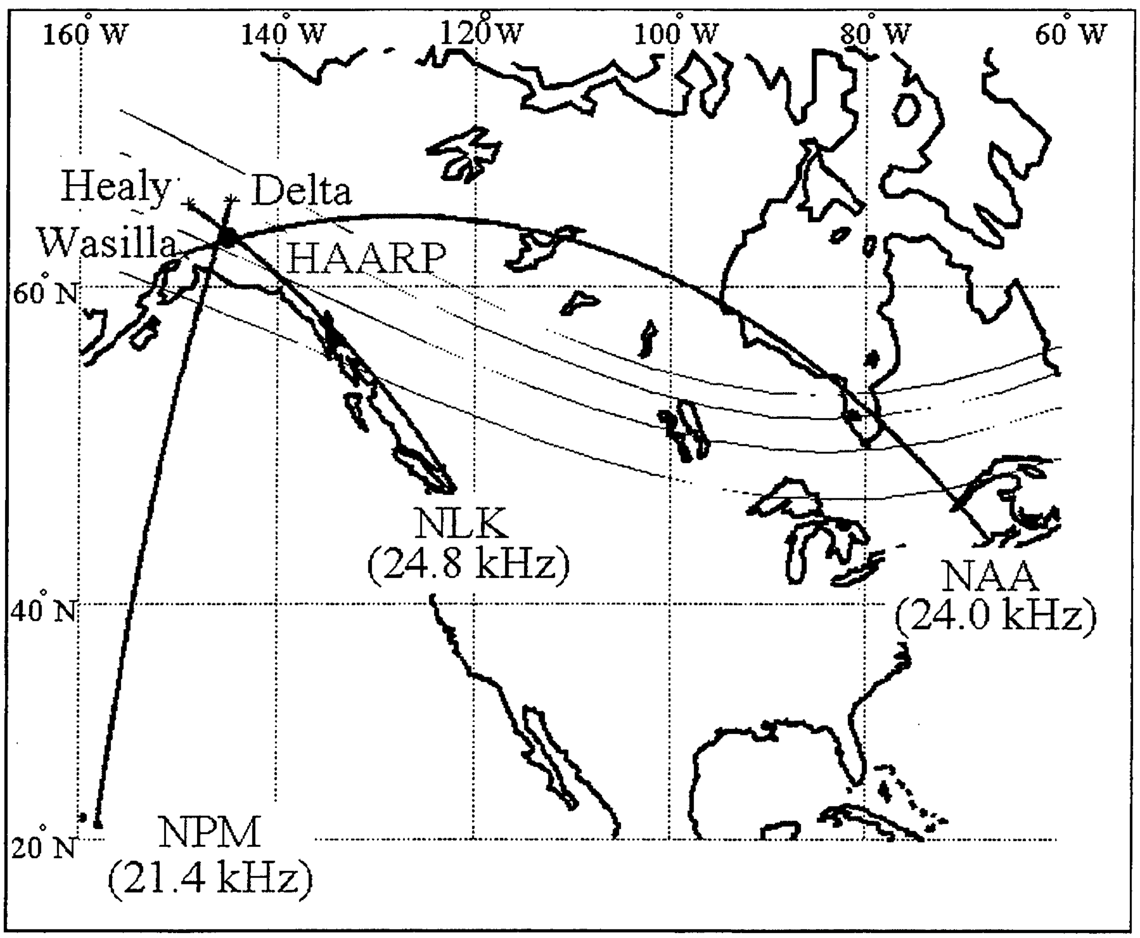

Figure 1. Great circle paths from United States Navy VLF sites to Alaskan receiver sites showing relationship of paths to the HAARP site location.

The changes in amplitude and phase are measured as the HAARP HF signal amplitude is 100% modulated (ON/OFF) by a square wave with frequency in the range 0.5 - 25 Hz for a time interval of 5 - 15 minutes. The phase and amplitude data are then analyzed using superposed epoch and spectral analysis techniques. At present it is not clear which square wave frequency is optimally suited for identification of the HAARP-induced changes in the shortest amount of time.

Another unanswered question concerns the ability of the VLF D-region diagnostics system to determine the altitude profile of the HAARP-modified collision frequency in cases in which the HF beam is tilted significantly away from the vertical direction. For example, some experiments call for the HF beam to be tilted as much as 30 degrees from the vertical. At this position the shape of the beam is no longer symmetric about its axis, and the HF waves have to propagate a longer distance through the ionosphere in order to reach a given altitude. Furthermore, the heated region is now shifted approximately 3 VLF wavelengths from its nominal position directly over the HF transmitter, and this shift might affect the VLF measurements at the fixed receiving sites.

As a result of these concerns, we proposed to use the HAARP facility to investigate the sensitivity of the HAARP VLF D-region diagnostics system to changes in the frequency of the square wave modulation of the HAARP HF transmitter and to changes in the position of the heated spot with respect to the vertical.

Due to the summer-time conditions in the D-region over HAARP during our experiments, we were not able to achieve sufficient signal-to-noise levels to measure meaningful phase data at any of our ground sites, and due to the use of relatively short integration times, we were only able to measure meaningful amplitude data from our least noisy ground site at Healy, Alaska.

Description of Experiment:

In order to address the issue regarding the HAARP VLF D-region diagnostics system's sensitivity to frequency, we were permitted to transmit a 3.3 MHz, X-mode waveform from the HAARP HF transmitter and vary the frequency of its modulation.

When the transmission is in the ON-cycle, the D-region of the Ionosphere absorbs the majority of the energy of this wave, increasing the electron collision frequency in that region in a matter of microseconds. When the transmission is in the OFF-cycle, the electron collision frequency recovers to its unheated state, also in a matter of microseconds.

Changing the electron collision frequency in the D-region changes the electrical conductivity, and the subionospheric VLF signals passing under the heated region are scattered. Because the measured amplitude and phase of the narrowband VLF signals at each of the ground sites consist of the vector sum of the direct and scattered waves, we expect to see a change in amplitude and phase of the signals when the electron collision frequency profile of the D-region over HAARP is changed.

In a campaign mode, our desire is to provide D-region collision frequency profiles to the HAARP control center in near real time. Thus we would like to minimize the time interval necessary to determine the profiles. This time interval depends primarily upon the amount of averaging at each site that is necessary to provide a useful signal-to-noise ratio for the scattered waves. Our summer experiments were designed to determine which HAARP square wave modulation frequency would minimize the time necessary for the diagnostics. We performed the square wave modulation experiment six separate times, setting the frequency of the square-wave modulation to 1 Hz, 5 Hz, 10 Hz, 15 Hz, 20 Hz, and 25 Hz, transmitting at each frequency for 4 minutes and 30 seconds. Data and results are provided in the following sections.

In order to address the issue regarding the HAARP VLF D-region diagnostics system's sensitivity to changes in the position of the heated region with respect to the vertical, we were permitted to transmit the same 3.3 MHz, X-mode waveform from the HAARP HF transmitter, aimed in a variety of directions. For this experiment, all transmissions were modulated with a 10 Hz square-wave (ON-OFF).

We performed this experiment five separate times, aiming the beam of the HAARP HF transmitter 30 degrees North, 30 degrees South, 30 degrees East, 30 degrees West, and directly vertical, transmitting in each direction for 5 minutes and 30 seconds. Data and results are provided in the following sections.

Data and Analysis:

Figures 2 through 5 on the following pages show the spectral analyses of our modulation frequency-varying experiments. The spectra in Figure 2 result from a superposed epoch analysis of the amplitude of the NLK signal measured at the ground site at Healy over a 10-second time period and show the spectral peaks of the NLK amplitude variation for the various HAARP modulation frequencies. It is clear that with 10 second averaging the NLK spectral peaks are close to the noise level. The most evident feature in these spectra is a 20 Hz local noise peak.

The spectra of Figure 3, which result from integration over a 15-second window, show the 15 Hz component clearly beginning to rise above the noise. The 10 Hz component is also present, but not as pronounced as the 15 Hz component. We cannot deduce anything about the 20 Hz component due to the local interference.

The spectra of Figure 4, now integrating over a 35-second period, show each of our modulation frequency components beginning to rise significantly out of the noise. And finally Figure 5, which integrates over the full 4 minutes and 30 seconds shows each of our frequency components quite clearly, each now well above the noise floor. It can be seen that a local noise source at 7 Hz is also present.

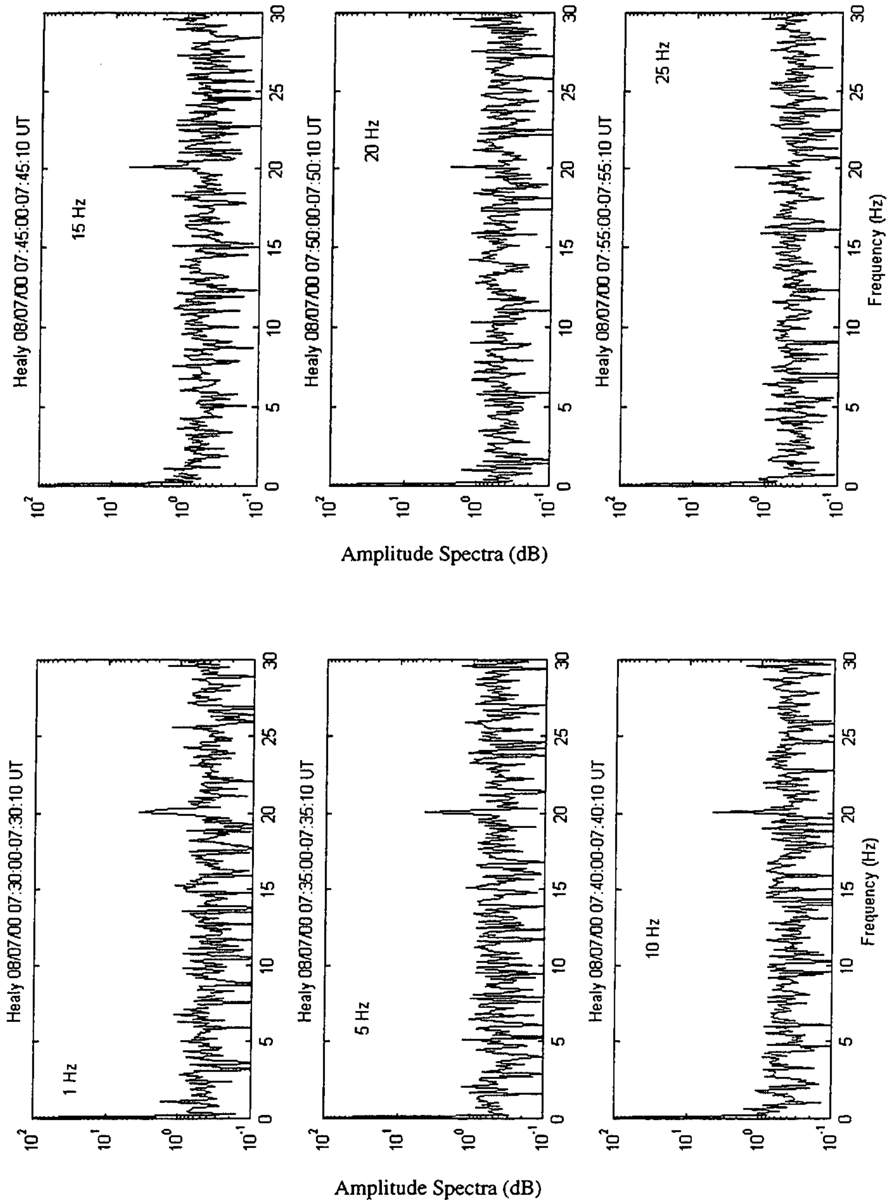

Figure 2. Superposed epoch analysis of the NLK signal amplitude received at Healy, AK. HAARP modulation frequencies (1, 5, 10, 15, 20, and 25 Hz) are shown in each panel. Integration period was 10 seconds. The 20 Hz spectral peak is caused by a local source.

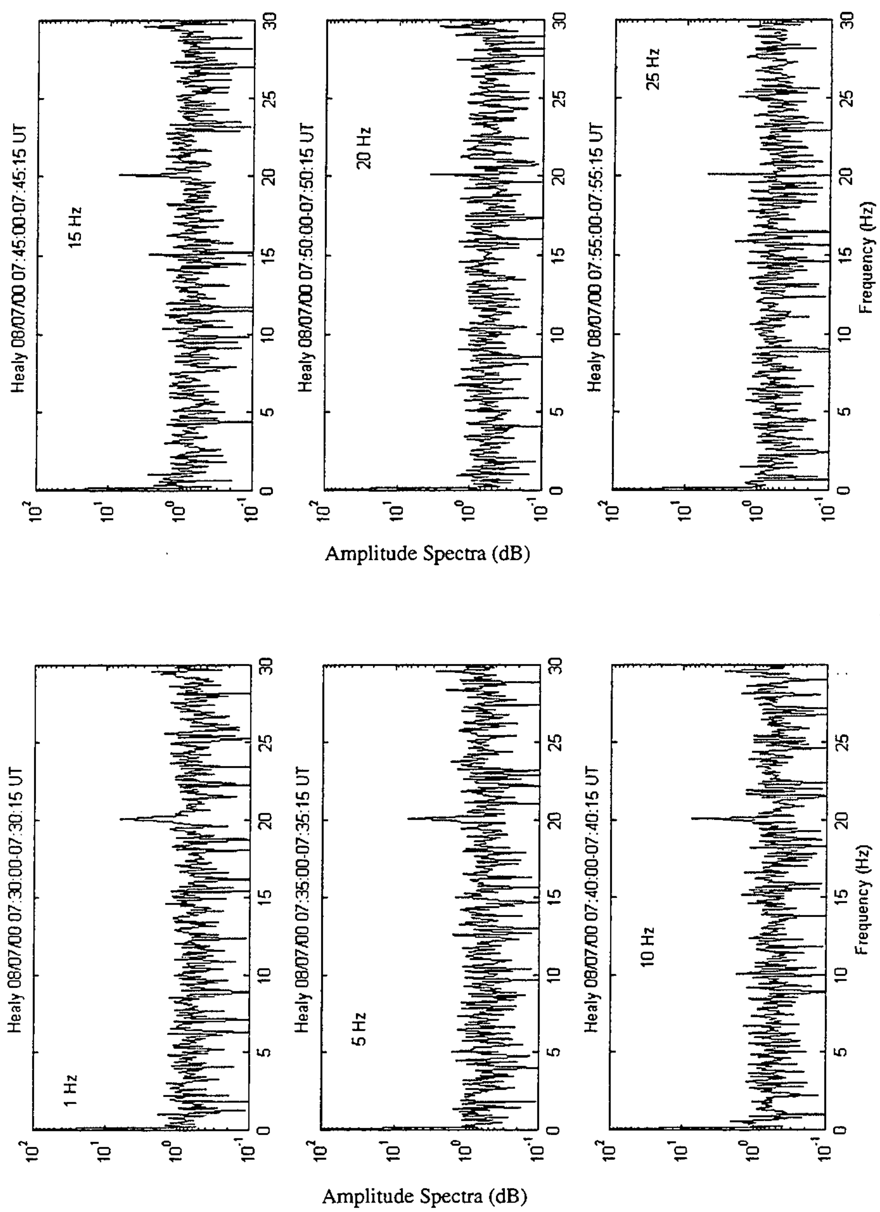

Figure 3. Superposed epoch analysis of the NLK signal amplitude received at Healy, AK. HAARP modulation frequencies (1, 5, 10, 15, 20, and 25 Hz) are shown in each panel. Integration period was 15 seconds. The 20 Hz spectral peak is caused by a local source. The 10 and 15 Hz are beginning to rise above the noise level.

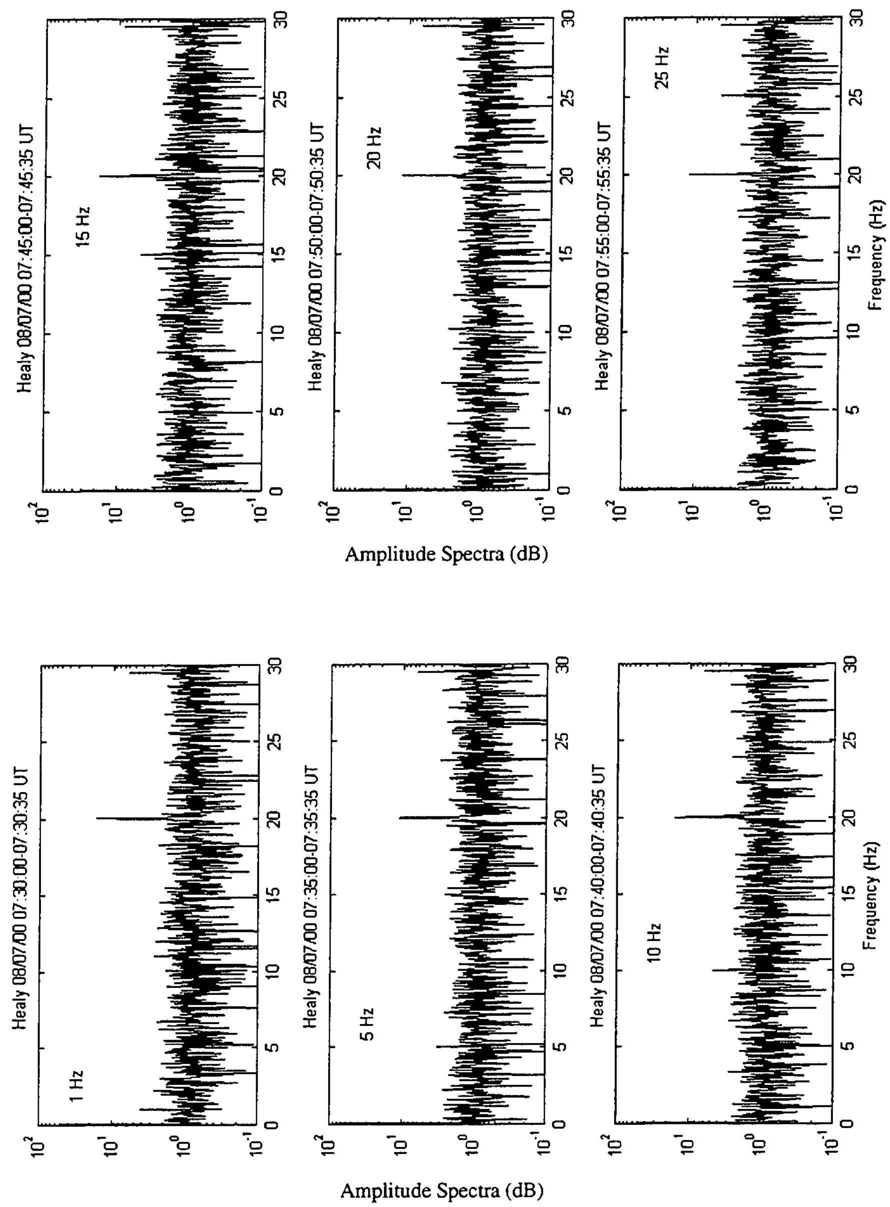

Figure 4. Superposed epoch analysis of the NLK signal amplitude received at Healy, AK. HAARP modulation frequencies (1, 5, 10, 15, 20, and 25 Hz) are shown in each panel. Integration period was 35 seconds. Each of the modulated frequency components are beginning to rise significantly above the noise. The 20 Hz spectral peak is caused by a local source.

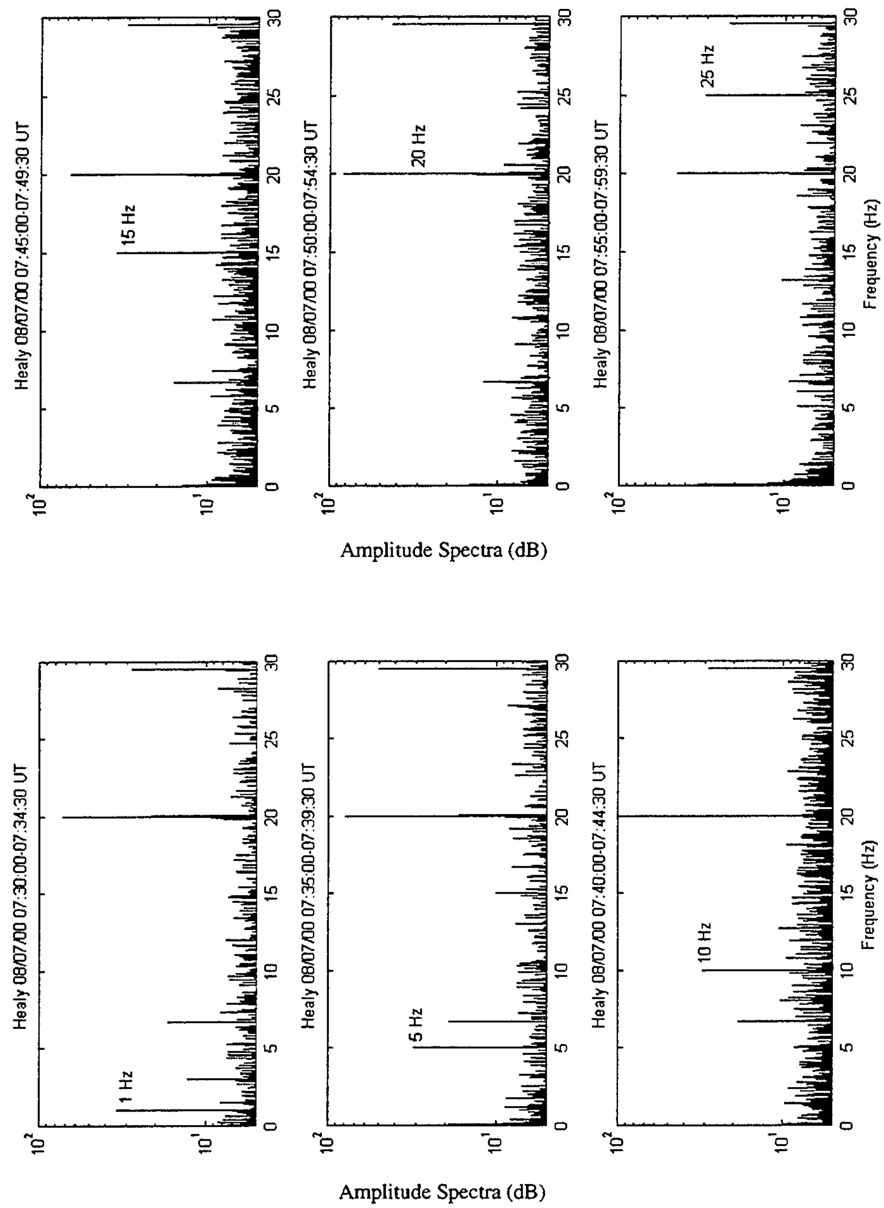

Figure 5. Superposed epoch analysis of the NLK signal amplitude received at Healy, AK. HAARP modulation frequencies (1, 5, 10, 15, 20, and 25 Hz) are shown in each panel. Integration period was 270 seconds. Each of the modulated frequency components are each well above the noise floor. The 7 and 20 Hz spectral peaks are caused by local sources.

Figure 6 (*cf.* p. 15) comprises our data to determine how the steering (placement) of the heated region will affect our HAARP D-region diagnostics system. However, our data are not complete due to the absence of meaningful phase measurements at the ground sites.

We see from Figure 6 that our amplitude spectral density shows the 10 Hz modulation component in the Vertical, 30 degrees North, and 30 degrees East positions. In the South and West directions, the 10 Hz component is present, but beneath the noise floor. However, it must be noted that the amplitude and phase measurements are not correlated. A low amplitude component does not imply a low phase component. It is possible that the phase spectral density for 30 degrees South and 30 degrees West could show a 10 Hz component. Unfortunately, we do not have useful phase measurements for this experiment for reasons discussed above.

Results:

After performing the modulation frequency-varying experiment at 1, 5, 10, 15, 20, and 25 Hz, we have shown through the data in Figures 2 through 5 that the optimal frequency range at the site at Healy for the square wave modulation of the HAARP HF transmitter is 10 to 15 Hz, weighted towards 15 Hz. We are not able to determine the onset of the 20 Hz component due to local interference.

After running the beam-directing experiment, we have shown in Figure 6 that our VLF D-region diagnostics system will be a valuable tool for experiments aiming the beam of the HAARP HF transmitter vertically, to the North, and to the East. For lack of meaningful phase data, we are not able to show conclusively that the VLF D-region diagnostics system will work for experiments aiming the beam of the HAARP HF transmitter to the South and to the West. Further experiments are needed to prove this conclusively.

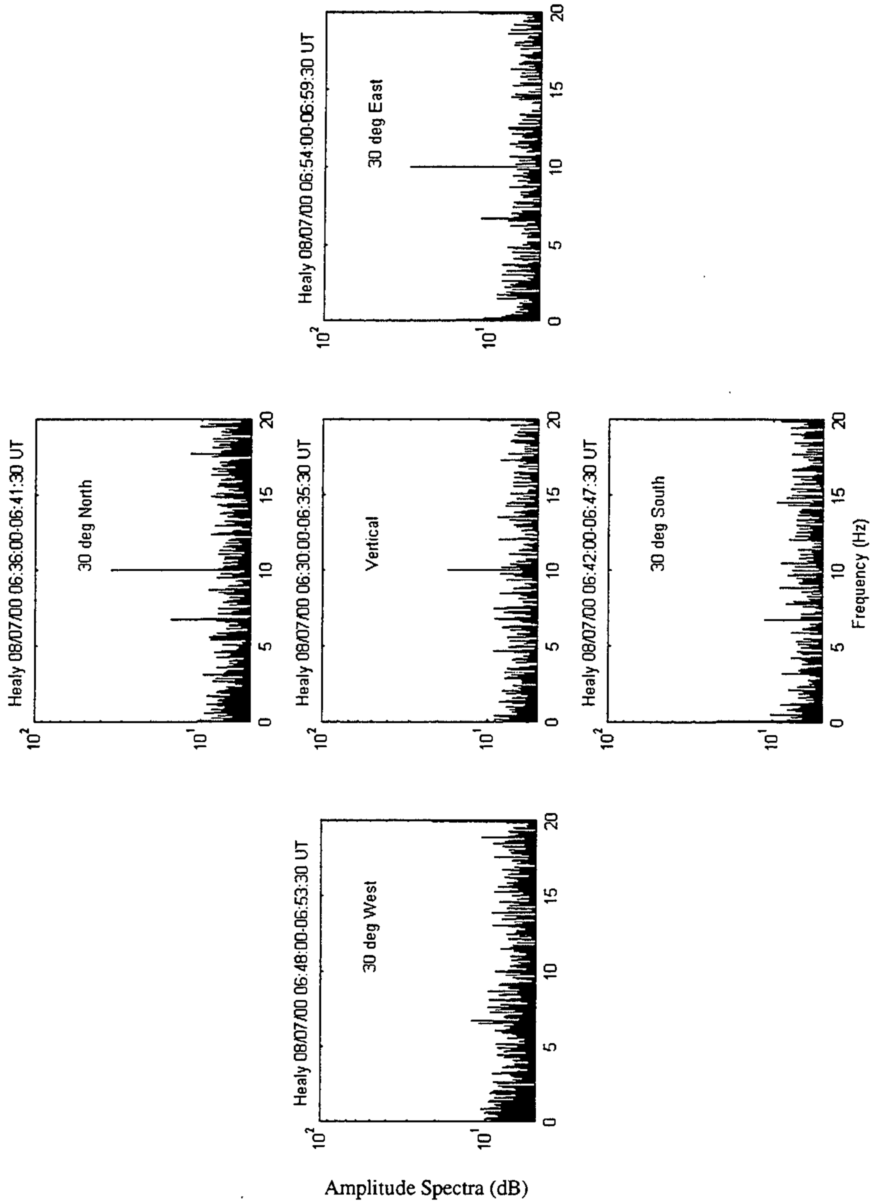

Figure 6. Superposed epoch analysis of the NLK signal amplitude received at Healy, AK. HAARP modulation frequency was 10 Hz with the HAARP transmit beam vertical then steered 30° to the North, South, West and then to the East. Integration period was 330 seconds. The 10 Hz modulation frequency is seen with the HAARP beam vertical and steered to the North and East.

SuperDARN Observations of HAARP Induced Ionospheric Irregularities

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For the HAARP Summer 2000 Student / Faculty Science Campaign, the SuperDARN radar was operated in a mode that provided both high-time resolution and high-spatial resolution. The operating mode concentrated on the area directly over the HAARP site by scanning over the six central beams and by returning to the beam directly over HAARP between each successive beam. That is, the scan sequence was: beam 5, beam 8, beam 6, beam 8, beam 7, beam 8, beam 8, beam 8, beam 9, beam 8, beam 10, beam 8. The sequence was repeated continuously with a dwell time of 2 seconds in each beam direction. Hence, the mode provided 4-second time resolution on beam 8 and provided full scans every 30 seconds. The range resolution was 15 km.

During the HAARP summer school observations, geophysical conditions were fairly active. The initial run of the first experiment did not produce any observable ionospheric irregularities. It is likely that because of the activity, the HF heater beam was suffering significant D-region absorption and little energy was reaching the F-region. The HAARP experiment was intended to investigate SEE emissions but, since no irregularities were being formed, no SEE emissions were being produced. After a period of time, the absorption appeared to decrease and ionospheric irregularities were observed by SuperDARN over the HAARP site. Coincident with the observation of irregularities, the SEE receiver began to observe emissions.

Figure 1 shows the range-time-intensity plot for the observations on the UT day August 7, 2000, during the period from 0000 UT to 0400 UT. This period corresponds to the late afternoon on August 6, 2000, in Alaska Daylight Time. The high-intensity patches of scatter at about 700 km range were produced by the HAARP-induced ionospheric irregularities. At times, the observed signal-to-noise ratio was in excess of 28 dB. In the beginning of the period, during the period of D-region absorption, the observed signal intensity was low; less than 10 dB SNR.

Figure 2 shows a plan view of the radar scatter at 0130 UT superimposed on a map of Alaska. The figure shows strong scatter located over the HAARP facility. The patch of scatter appears to be broader in azimuth extent than in range extent. This is due to the inherent convolution of the radar antenna beam pattern with the actual patch of ionospheric irregularities.

This brief experiment demonstrates the value of SuperDARN as a diagnostic instrument to observe and evaluate effects produced by the HAARP high frequency transmitter.

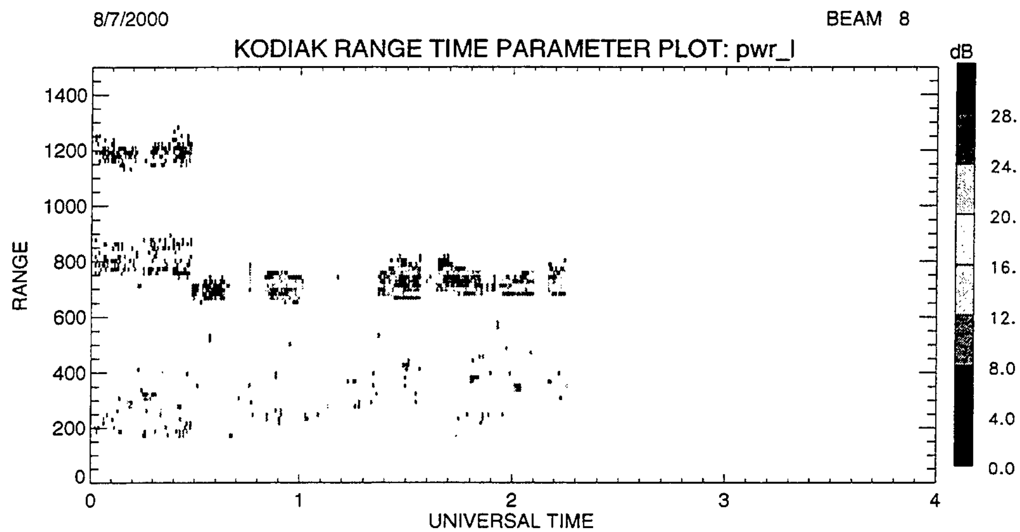

Figure 1. Range time intensity plot for 0000 to 0400 UT on August 7, 2000.

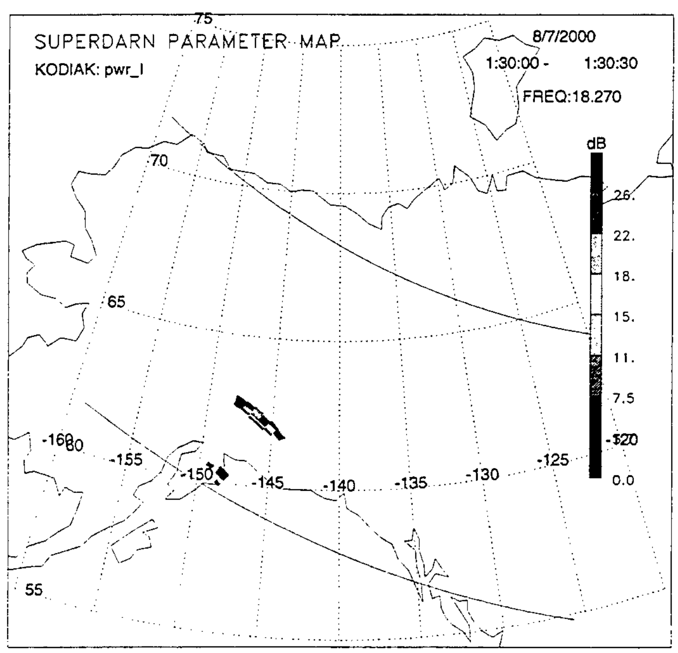

Figure 2. Map of HAARP induced irregularities over Alaska.

Telescopic Measurements of Heater-Induced Airglow at the HAARP Facility

Umran. S. Inan
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Stanford, CA 94305

Objectives:

We proposed to conduct telescopic measurements of the optical emissions created by HAARP HF heating of the ionosphere. With the narrow field of view (0.72° x 0.9°) of a telescopic system we will be able to determine whether there is fine structure in the optical airglow emissions. We are able to view an object 100 km away with a resolution of ~3m. Since the lateral extent of the ionospheric region heated by the HAARP HF transmitter is ~30 km, our narrow field of view will be completely within the heated region. Strapped onto the telescope is a wide field-of-view camera with a FOV of 24 km x 31 km at 100 km altitude. The telescope will be aimed so that at least one edge of the heated region is within the wide FOV. Although airglow observations of heaters have been conducted in the past [see references], our proposed observations would be the first attempt to look for fine structure within the heated regions. Observing either the absence or presence of structure would be an important scientific contribution and would give additional insight into the atmospheric makeup of these heated regions. Although the main lobe of the HAARP HF heater is quite broad, one might expect fine structure due to ambient electron density variations. It is also possible that small variations in the radiation pattern within the main lobe may be detectable.

Editor's Note: This experiment, proposed for part of the Summer 2000 Student / Faculty Science Campaign was first attempted at HAARP in April 2000. However, the experiment wasn't conducted as part of the Student / Faculty Campaign as the August lighting conditions precluded meaningful observations. The experiment was conducted successfully by Elizabeth Gerken as part of HAARP's Fall 2000 Science Campaign. The results from the Fall Campaign will be reported elsewhere.

Description of Components:

Our proposed system consists of a telescope with two cooled scientific bare CCD cameras - one mounted at the image plane of the telescope and the other bore-sighted on top for a wide field of view (14° x 18°). The system uses a Meade Starfinder telescope which is a 16" aperture, f/4.5 Dobsonian-mounted, Newtonian reflecting telescope. Additionally there is a photometer aligned with the field of view of the cameras and mounted on top. Both the cameras and the photometer are narrowband-filtered to allow either the near infrared N2 first-positive lines, the 630nm atomic oxygen line, or the hydroxl lines to be selected for viewing. The cameras are Princeton Instruments VersArray 512B digital CCD systems with thermoelectric Peltier cooling, 512X512 pixel format, and binning and subregion readout modes. Frames from the camera are sent directly to a computer interface with accompanying software for real-time acquisition, display, and data processing. The interface has a 16 bit A/D converter with dual speeds of 100kHz and 1MHz. The higher speed can be used when focussing the system and the slower one for low-noise readout during data acquisition. The camera will be integrated for several seconds (up to 30sec) in order to be able to view the relatively dim airglow levels of 20-100 Rayleighs. Analysis of the system sensitivity and previous measurements of HF heater-induced airglow emissions indicate that our system can detect emissions produced at the current operating power levels of the HAARP HF transmitter.

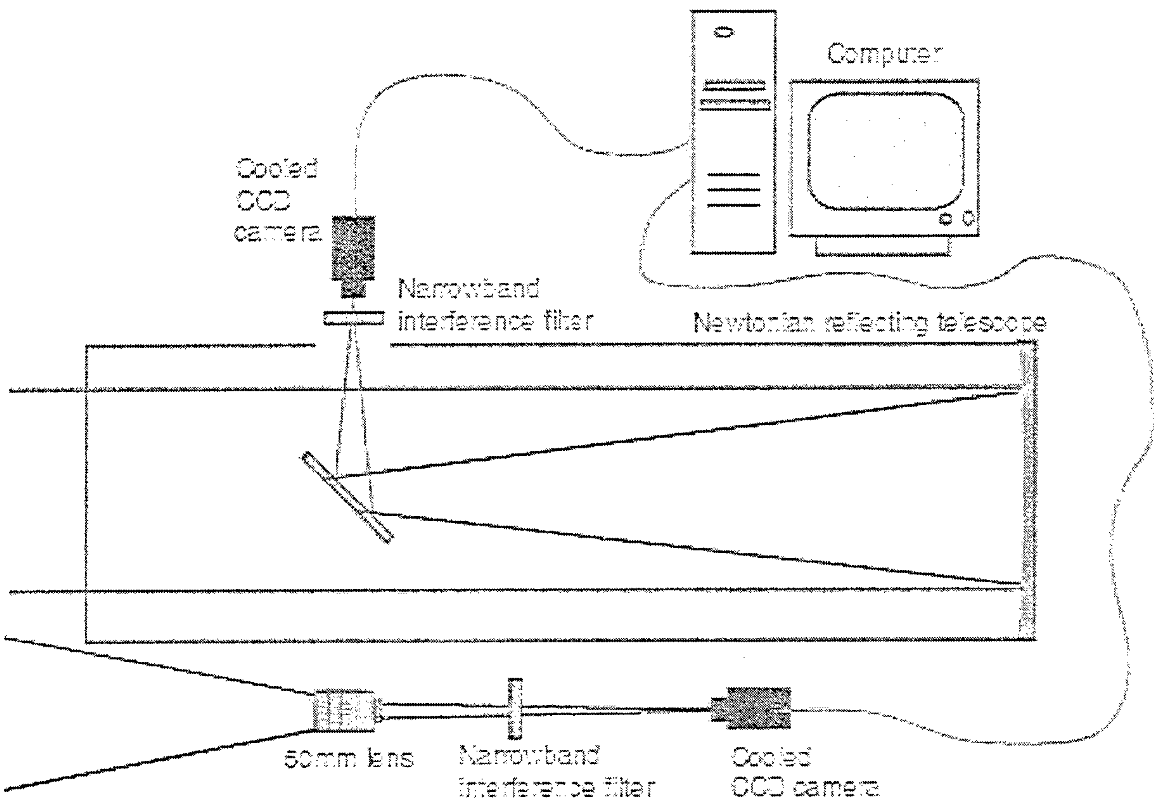


Figure 1. Diagram of proposed telescopic imaging system

Preliminary Results:

The telescopic system with intensified CCD cameras has previously been deployed for two sprites campaigns (1998 and 1999) at the Langmuir Laboratory with great success (see Figure 1). The high spatial resolution images captured with the telescope revealed for the first time the presence of detailed fine structure in sprites. The photometer adds temporal high resolution so that the relatively slow frame rate of a video camera is not a limitation. Example data from these campaigns is shown in Figure 2.

This telescopic system was deployed at HAARP in April 2000. For this initial airglow survey, the 630nm oxygen line was observed with narrowband interference filters on both cameras. Although this line has a relatively long lifetime of 110ms and would be smeared structurally over a 30s integration period, it was selected because it is a well-characterized emission over heaters such as at Arecibo (Bernhardt et. al., 1989). The heater was pulsed on and off at 5 min intervals at 8 and 4.5 MHz in both X and O mode to probe the ionosphere. The campaign lasted six nights; however the experiment was only set up for two nights due to aurora and snow. Initial studies of the data gathered from this campaign do not show detectable airglow emissions. This corresponds to simultaneous observations carried out at Poker Flats by Dr. Davis Sentman. It is difficult to determine the cause of the absence of airglow emissions in the 630nm line on the basis of such a small data set - atmospheric absorption, diffuse aurora, thin clouds, and faint moonlight could all have played contributing roles. This campaign needs to be conducted for a longer time period (two weeks) and repeated several times in conjunction with the other diagnostics at HAARP such as the riometer, ionosonde, magnetometer and collision rate profiles obtained from VLF signals.

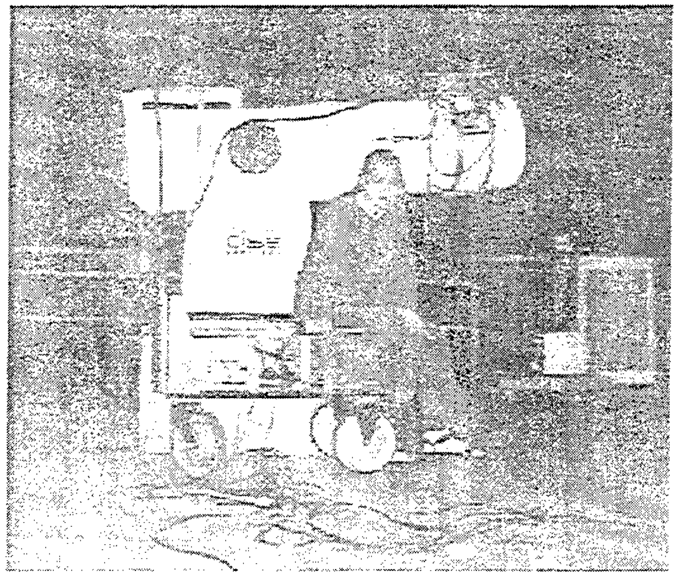


Figure 2. The telescopic system as operated at Langmuir

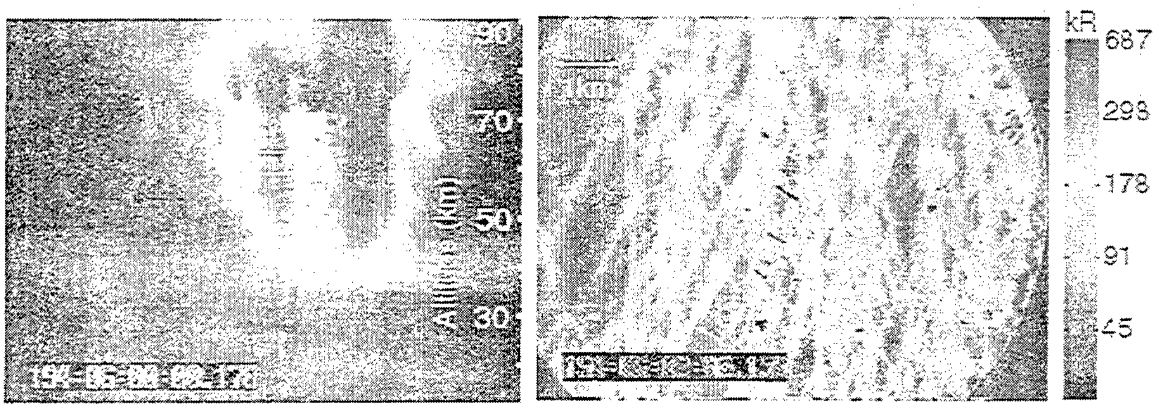
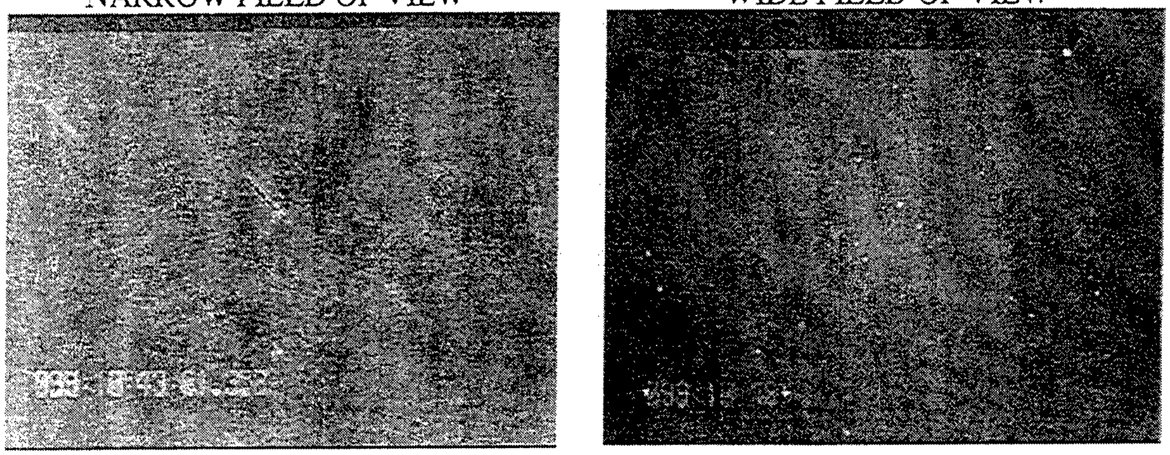


Figure 3. Example data from the telescope. The left frame shows the wide field of view (FOV) and the right frame shows the telescopic image. The narrow FOV corresponds to the rectangle in the wide FOV image

NARROW FIELD OF VIEW WIDE FIELD OF VIEW



Day 99 10:43 UT, 38 sec exposure Day 99 10:48 UT, 38 sec exposure

Figure 4. Example data from the April 2000 HAARP

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Polar Mesosphere Summer Echoes Observations Using the HAARP High Frequency Transmitter

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Objective:

We wanted to take advantage of the HAARP (High Frequency Active Auroral Research Program) to focus its resources on aeronomic studies in the polar summer mesosphere. Our first goal was to obtain echoes at one or more HF frequencies from polar mesospheric clouds (PMC), also called noctilucent clouds (NLC). These clouds are the highest clouds on Earth and form in a very cold region, at temperatures sometimes less than 120 K. Such radar echoes, know as polar mesosphere summer echoes (PMSE), have been first reported at the SURA facility in Russia in the frequency range of 8-9 MHz but after detecting them no more studies were conducted due to limitations in their system. Theoretical analysis indicated to us that it should be possible to detect PMSE at the entire HF range in which the HAARP transmitter works (2.8-10 MHz). These measurements are the first made in Alaska with the flexible and versatile HAARP system that allowed us to perform multiple experiments continuously. Some of the features of the HAARP system are: electronic phase array beam steering, wide transmitter frequency coverage, and a variable effective radiated power. Therefore, in addition to detecting PMSE we were able to observe the PMSE variations at different frequencies, transmitted powers, and antenna pointing directions. This report briefly describes the experiments we performed at the HAARP facility and summarizes the preliminary observations that resulted from this first successful campaign.

Observation Technique:

The system used in our experiments included two different antennas: the powerful HAARP transmitting antenna was used for transmission and the digisonde transmitting antenna was used for reception. Additional equipment was brought to the facility in order to be able to use the digisonde transmitting antenna for reception as well as an acquisition system.

The HAARP transmitting antenna is a phased array transmitter and is designed to transmit a narrow beam of high power radio waves at allocated frequencies from 3.155 to 8.1 MHz. We were able to change the transmitted power in submultiples of 96 kW, i.e., 960 kW (maximum power available), 864 kW, 768 kW, etc. Transmissions from each dipole can be adjusted to obtain different antenna pointing directions; the antenna can be tilted to a maximum of 30° from the vertical in all directions. There are other capabilities that can be implemented at the HAARP facility such as CW, AM, linear FM/CW, single pulse modulation, and simultaneous multi-frequency transmissions that we are hoping to implement next summer season.

The digisonde transmitting antenna has 4 electrically separate or separable elements with vertical rhombic radiation characteristics. One-half of the antenna was used for reception and connected to an acquisition system (i.e., receiver, computer, etc) brought for that purpose. Using the software available we were able to see the echoes in real time, to save all raw data on the hard drive, and later to make compact disk backups.

Experiments:

The experiments were conducted during the period August 1st to August 7th, 2000 covering approximately 18 hours of operation around noon local time. The time of operation was chosen with the criteria that previous VHF PMSE observations showed a tendency to occur predominantly between 10:00 and 13:00 hours local time. We used 10 μs pulses with a long interpulse period of 20 ms to ensure we were not contaminating the collected signal with echoes from higher heights. We found that 20 ms was a good compromise for that purpose.

As it was mentioned above, the transmitting system has especially flexible operating characteristics that allowed us to perform multiple experiments with a delay of only 30 seconds once the experiment has been programmed in the main computer. This means that when we refer to 5 minutes observations we are talking about 4 minutes 30 seconds observations with a 30 seconds no-transmission period during the change of experiments.

Our first task was to see if we could detect PMSE. After they were detected, we performed three experiments. The first one changed the transmitted power, the second changed the frequencies and the third changed the antenna pointing directions. We present and discuss the preliminary results in the next section.

The plots presented in the next section were developed by coherently averaging over 100 pulses to improve the S/N (signal-to-noise). The data points were available at each of 127 heights. The S/N values were calculated by dividing the signal power by the average power calculated at heights between 40-60 km where PMSE were not present. The vertical dashed lines on the plots represent an experiment change.

Preliminary Results:

Observations started on August 1st, 2000 but we could not detect PMSE on this day. During the campaign PMSE were observed 4 out of 6 days. This result is not surprising as we were at the end of the summer season and PMSE should be disappearing. The first successful observations of PMSE were obtained on August 2nd, 2000.

The next three figures can be considered as representative examples of summertime HF echoes observed over Gakona during August 1-7, under three different setting conditions. These figures are color contour plots of S/N (dB) vs. height (km) and time (hours). As you will see in the following plots, PMSE is characterized by a thin layer centered around 86 km and in some occasions occurs as a double layer as has been observed in previous experiments at VHF.

Figure 1 shows the results for the first experiment in which the transmitted power was varied. We started with the maximum possible power, 960 kW, and went to 864 kW, 768 kW, 672 kW, and 576 kW for 10 minutes in each case. The gap corresponded to a failure in the program that controls the experiments. It was fixed and started again at the point of failure. The results are surprising as there is not much difference in the intensity of the echoes observed even though the power was changed by almost 400 kW.

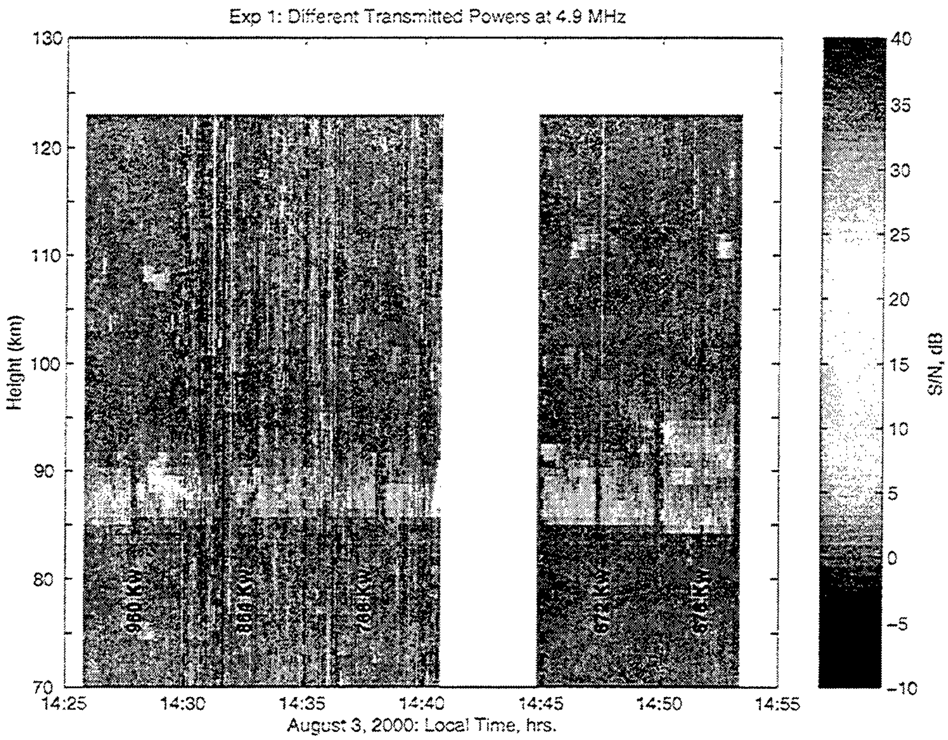

Figure 1. S/N variations observed at different transmitted powers keeping the frequency at 4.9 MHz.

In the second experiment the HAARP HF transmitter was cycled through a sequence of three frequencies between 3.155 and 8.1 MHz. The frequencies chosen were 3.275, 4.9 and 7.6 MHz. We started with 4.9 MHz and once we had the PMSE detected for 25 minutes we changed the frequencies following the sequence 7.6, 3.276, 4.9, 3.276, and back again to 4.9 MHz. Each frequency was transmitted for 10 minutes maintaining the pointing direction of antenna to vertical. The results of this experiment are shown in Figure 2. By looking at the data we can see that significant changes in intensity were observed as the frequency was varied. Two layers are always observed at 4.9 MHz and the second layer disappears at 7.6 and 3.275 MHz. Another feature observed in this figure is the occurrence of a layer above 120 km when we are transmitting at 3.275 MHz. This could be due to sporadic E or 3.275 MHz irregularities. Preliminary explanations for the lack of correlation between frequency and power received could be related to the different characteristics of the system when working at different frequencies. For example, the antenna directivity increases from 14 dB at 3 MHz to 24 dB at 10 MHz, the main lobe beamwidth decreases from 30° at 3 MHz to 9° at 10 MHz, etc. We are very surprised to see a decrease in echo at 86 km going from 4.9 to 3.276 MHz. A turbulent echo source clearly would have a higher echo strength at longer wavelengths. Scattering from sharp changes in the index of refraction is less well understood but we expected a similar increase at low frequencies. However it is important that no sidelobe exists perpendicular to B at 120 km range. Unfortunately since we used the digisonde antenna, no sporadic E measurements are available.

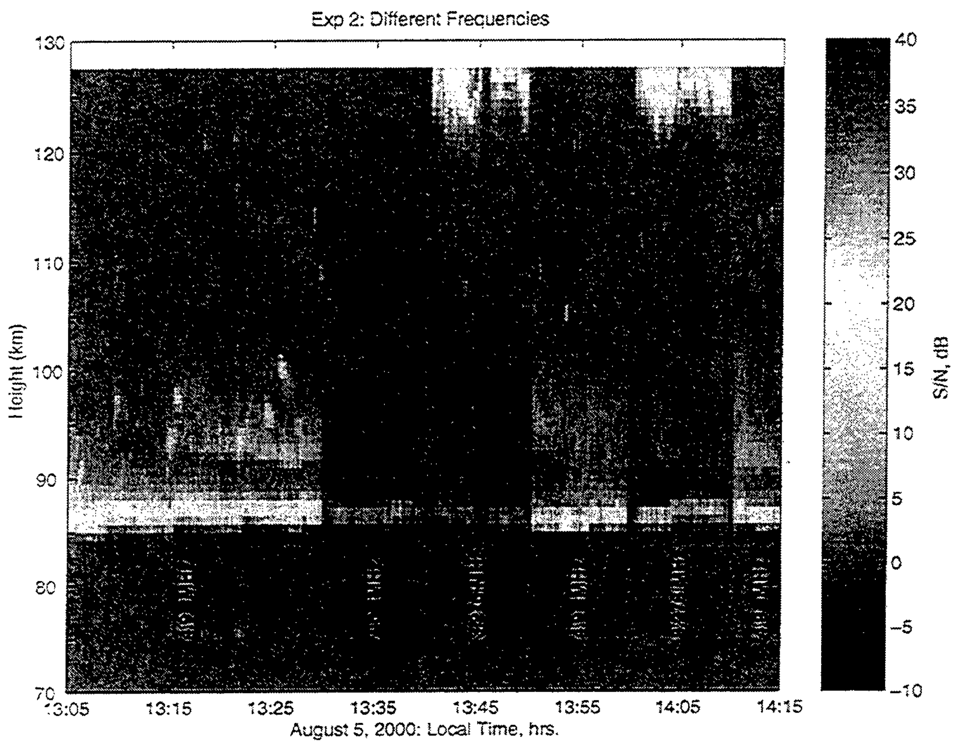

Figure 2. S/N variations observed at different frequencies.

In the third experiment we changed the antenna pointing directions, maintaining the transmitting frequency at 4.9 MHz. We started with the antenna pointing in the vertical direction followed by tilting the antenna to North 5°, North 30°, East 5°, East 30°, and going back to vertical. We changed directions every 5 minutes. The results presented in Figure 3 reflect this experiment. The presence of two layers is obvious for the vertical beam and when the antenna was tilted 5° to the North and East. We cannot observe the second layer when the antenna was tilted at 30° to the North and East. We can then

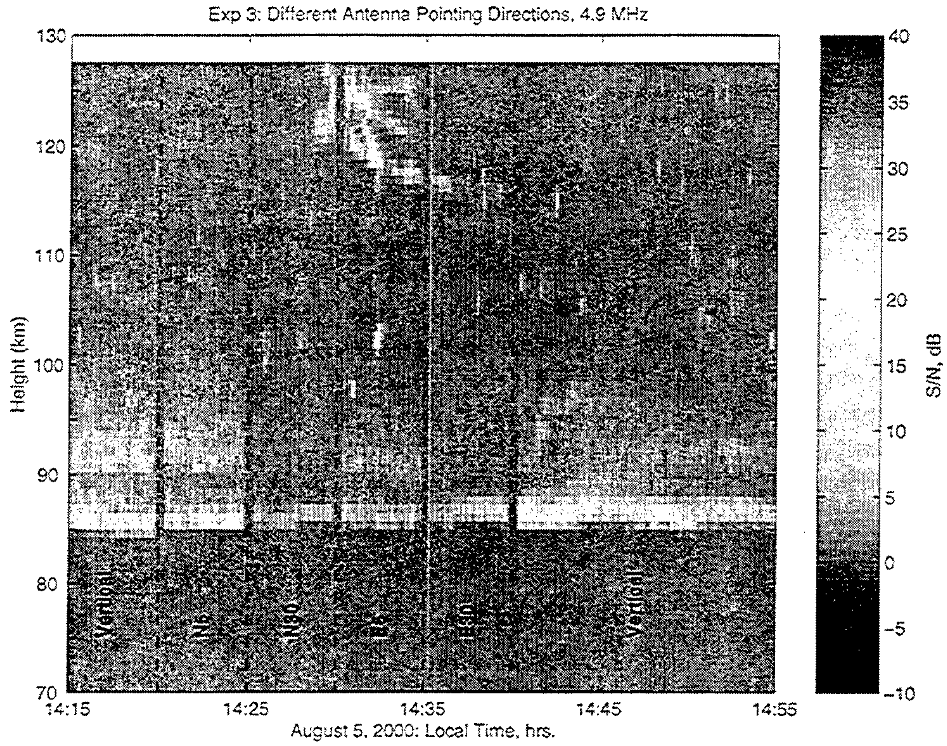

Figure 3. S/N variations observed at different antenna pointing directions.

calculate the aspect sensitivity of PMSE. These results will give us information on the dependency of echo power on the pointing direction of the radar beam relative to the vertical and a reasonable indication of the scattering processes. Just by looking at the data we can say that the backscatter returns are stronger when the radar is closer to the zenith.

Summary:

We were successful observing PMSE for the first time in Alaska at HF and only the second ever. We have presented results comparing PMSE observations varying three parameters: transmitted power, frequency and antenna pointing directions. We have been able to observe PMSE intensity differences with each change made on the system. We will now concentrate on exploiting the database collected the last August, in order to learn more about this intriguing phenomenon.

During this campaign PMSE have been observed at the end of the summer season. We would like to run a campaign this coming March in which PMSE are not expected so we can confirm that the echoes observed in this first campaign are PMSE. We also look forward to better coverage next year, with observations starting at the beginning of the summer season and during their maximum peak of occurrence (first week of July) as well as to increase S/N with the planned implementation of pulse coding. If we continue to monitor these echoes, this facility could be used to monitor potential markers of global change due to the strong correlation found of the increasing NLC with warmer global temperatures.

Experimental Comparison of Two Heating Wave Modulation Schemes on ELF/VLF Wave Generation Efficiency

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Abstract:

Through ohmic heating by the amplitude-modulated HF heating wave, the conductivity and thus the current of the electrojet is modulated to set up the ionospheric antenna current. It has been demonstrated that such an antenna current can generate ELF / VLF waves. The issues considered in the research, however, are the generation efficiency and signal quality, which have been shown by the results of numerical [Kuo el. al., 1998] and theoretical [Kuo el. al., 2000] studies to depend strongly on the HF heating wave modulation scheme. In the theoretical study, four amplitude-modulation schemes: (1) rectangular wave, (2) beat wave, (3) half-wave rectified wave, and (4) triangular wave were examined and compared. The results of the analysis conclude that the beat wave scheme generates the best quality signal, which has the lowest harmonic content. The half-wave rectified wave modulation scheme is the most efficient one to generate an ELF / VLF signal at the modulation frequency.

In the summer of 2000, HAARP organized a student / faculty heating campaign at Gakona, AK. It provided us an opportunity to confirm the theoretical predictions. There, we have carried out an experiment on ELF / VLF wave generation using two heating wave modulation schemes: (1) rectangular wave and (2) half-wave rectified wave. The other two schemes considered in the theory could not be implemented easily and will be investigated in the future. The experiment was conducted by using 100 Hz (ELF) and 6.25 kHz (VLF) modulations to confirm the theoretical prediction [Kuo, *et al.*, 2000] that the half-wave rectified wave should be more efficient (~3dB) than the rectangular wave. The intensities of ELF and VLF radiation generated by the two modulation schemes were compared and the results were shown to agree very well with the theoretical prediction.

S. Kuo, D. Bivolaru, M.C. Lee, P. Jastrzebski, R.J. Riddolls, and D. Sentman

Introduction:

It has been suggested that a powerful HF wave could significantly perturb the local electron temperature in the lower ionosphere through an Ohmic heating process [Willis and Davis, 1973; Getmantsev et. al., 1974; Stubbe and Kopka, 1977; Kapustin *et al.*, 1977]. Thus, the electrojet current in the lower ionosphere can be modulated by the amplitude-modulated HF wave due to the dependence of plasma conductivity on the electron temperature. Generation of ULF/ELF/VLF waves by the modulation current in the electrojet has been studied experimentally [Stubbe, *et al.*, 1981 and 1985; Barr and Stubbe, 1984a, b and 1991a, b; Ferraro *et al.*, 1982, 1984; James, *et al.*, 1984; Lee *et al.*, 1990; McCarrick *et al.*, 1990; Barr *et al.*, 1991] as well as theoretically [Stubbe and Kopka, 1977; Stubbe, *et al.*, 1982; Kuo and Lee, 1983; Papadopoulos and Chang, 1985; Papadopoulos *et al.*, 1990; Kuo and Lee, 1993; Kuo, 1993; Kuo *et al.*, 1998 and 2000]. The frequencies of radiation are controlled by the modulation frequency of the amplitude-modulated HF heating wave.

The generation efficiency and signal quality are critical issues in this research area, which have been shown, by the numerical [Kuo *el. al.*, 1998] and theoretical [Kuo *el. al.*, 2000] results, to depend strongly on the modulation scheme, mode type, carrier and modulation frequency, and power of the heating wave. Therefore, a systematic experiment on the generation of ELF and VLF waves by the HF-heating-wave-modulated polar electrojet is needed. The experimental results serve to verify the theoretical and numerical predictions and to guide new theoretical efforts.

Theoretical Basis:

Considering a modulation function of the heating power in a general form as

$$M(t) = \sum_{k=0} M_k \cos k(\omega_1 t + \varphi) \tag{1}$$

where $\omega_1/2\pi = f_1 = 1/T_1$ is the modulation frequency and the phase φ is assumed to be the same for all of harmonic components; moreover, $M_0 = 1$ is assumed to keep the average heating power independent of the modulation scheme.

Eq. (1) indicates that a modulation of the electron temperature at harmonics of the modulation frequency is also introduced by the modulation source, in addition to that caused by the nonlinearity of the plasma. Therefore, the signal quality and generation efficiency of ELF/VLF waves depend strongly on the HF wave modulation scheme. These points are exemplified in the following by comparing the two factors $N_n = (M_n/M_1)^2$ (or $N = \sum_{n=2} N_n$) and $\eta_1 = M_1^2$ for three modulation schemes applied on the HF heating wave. These two factors are defined as the indicators on the nth harmonic noise level N_n (or the total noise level N and signal quality $\propto N^{-1}$) and the efficiency η_1 of a modulation scheme.

Rectangular wave modulation:

The field amplitudes of the HF heating waves are modulated by a rectangular wave in the ELF/VLF frequency range. Thus, the power modulation function is given by

$$M_r(t) = (T_1/T)\Sigma_n P_{T/2}(t-T/2-nT_1) = [1 + 2\Sigma_{k=1} \text{sinc}(k\omega_1 T/2)\cos k(\omega_1 t+\pi T/T_1)] \quad (2)$$

where $P_a(x) = 1$ for $|x| < a$ and 0 for $|x| > a$ is a rectangular pulse function, T_1 is the modulation period, and T/T_1 is the percentage duty cycle.

Thus, the coefficients M_{rk} and the phase angle φ in (1) are obtained in this case to be: $M_{rk} = 2\text{sinc}(k\omega_1 T/2)$ for $k \geq 1$, and $\varphi = \pi T/T_1$. It shows that the modulation is not sinusoidal. Only a small fraction of the total modulation contributes to the modulation at the fundamental frequency ω_1. The two indicators are given by

$$N_n^r = \sin^2(n\omega_1 T/2)/n^2\sin^2(\omega_1 T/2) \text{ and } \eta_1^r = (4/\omega_1 T)^2\sin^2(\omega_1 T/2) \quad (3)$$

For $T= T_1/2$ case, all of the even harmonic components are eliminated, i.e., $N_{2m} = 0$ for integer $m \geq 1$. Thus,

$$N_{2m+1}^r = (2m+1)^{-2},\ N^r = \pi^2/8 - 1 = 0.2337\ ,\text{ and } \eta_1^r = (4/\pi)^2 \quad (4)$$

Beat wave modulation:

The power modulation function is given by

$$M_b(t) = 1 + \cos(\omega_1 t +\varphi) \quad (5)$$

where φ is an arbitrary phase angle.

Thus, $M_{b1} = 1$, and $M_{bk} = 0$ for $k \geq 2$, and the two indicators

$$N_n^b = 0,\ N^b = 0,\text{ and } \eta_1^b = 1 \quad (6)$$

Modulation by half-wave rectified wave:

In this case, the power modulation function is

$$\begin{aligned} M_h(t) &= 1 - \cos 2\omega_1 t - (16/\pi)\Sigma_{n=0}\{(2n+1)[(2n+1)^2-4]\}^{-1}\sin(2n+1)\omega_1 t \\ &= 1 - (16/\pi)\Sigma_{k=1}[(\sin k\pi/2)/k(k^2-4)]\cos k(\omega_1 t-\pi/2) \end{aligned} \quad (7)$$

Thus, $\varphi = -\pi/2$ and $M_{hk} = -(16/\pi)[(\sin k\pi/2)/ k(k^2-4)]$ for $k \geq 1$. The two indicators are given by

$$N_n^h = [3\sin(n\pi/2)/n(n^2-4)]^2,\ N^h = (\pi/3)^{1/2}/25\ ,\text{ and } \eta_1^h = (16/3\pi)^2 \quad (8)$$

where $N_2 = (3\pi/16)^2$.

From (4), (6), and (8), we obtain the following ratios

$$\eta_1{}^r : \eta_1{}^b : \eta_1{}^h = 1 : (\pi/4)^2 : (4/3)^2$$

and (9)

$$N^r : N^b : N^h = 0.2337 : 0 : 0.0409$$

The results presented in (9) clearly indicate that the *half-wave rectified wave modulation scheme* is the most efficient one and the *Beat wave modulation scheme* produces signals of the highest quality.

Experiment and Results:

We carried out an experiment on ELF / VLF wave generation using two heating wave modulation schemes: (1) rectangular wave and (2) half-wave rectified wave. The beat wave scheme considered in the theory could not be implemented easily and will be investigated in the future. The experiment was conducted by using 100 Hz (ELF) and 6.25 kHz (VLF) modulations to confirm the theoretical prediction [Kuo, et al., 2000] that the second scheme should be more efficient (~3dB) and better in signal quality than the first one.

The experiment using a X-mode cw HF heating wave was conducted on August 7, 2000 from 5:00 to 7:30 UTC for three half hour intervals (5:00 to 5:30, 6:00 to 6:30, and 7:00 to 7:30). In each half-hour period, two modulation schemes with the rectangular wave modulation first were run alternatively for 5-minute intervals. The modulation frequencies for the three 10 minute slots were 100 Hz, 6.25 kHz, and 100Hz, respectively. The peak radiated powers of each antenna used for the rectangular wave and half-wave rectified wave modulation schemes were 5 kW and 10 kW, respectively, so that the average powers used for the two schemes were the same. Thus, the experimental results could be compared directly.

Unfortunately, the auroral electrojet was absent during the first two hours. Therefore, no ELF and VLF radiation were measured during that time period. However, a weak electrojet appeared in the third hour and both ELF and VLF radiation at the respective modulation frequencies were detected. Shown in Figures 1a and 1b are the amplitudes of the x and y components of the ELF (100 Hz) wave magnetic field detected in the time intervals: 7:00 to 7:10 and 7:20 to 7:30. The VLF (6.25 kHz) wave was detected in the time interval: 7:10 to 7: 20. The power of the radiation is presented in Figure 2. The results clearly demonstrate that whenever the modulation is switched from the rectangular wave to the half wave rectified wave, a significant increase in the signal intensity occurs. In the ELF wave case, the increase in the signal power intensity is more than 3 dB. The intensity increase in the VLF wave case is about 2.5 dB.

Conclusion:

The large fluctuations appearing in the ELF signals were the result of a weak auroraL electrojet. Therefore, the actual increase in the ELF signal intensity by switching the modulation from the rectangular wave to the half wave rectified wave is not certain. Nevertheless, the significant difference in the signal intensities of the two cases and the repeatable results provide no ambiguity in the conclusion that the half wave rectified wave modulation scheme is more efficient than the rectangular wave modulation scheme, confirming the theoretical prediction.

The intensities of higher harmonic signals were too weak to be used reliably for the assessment of signal quality.

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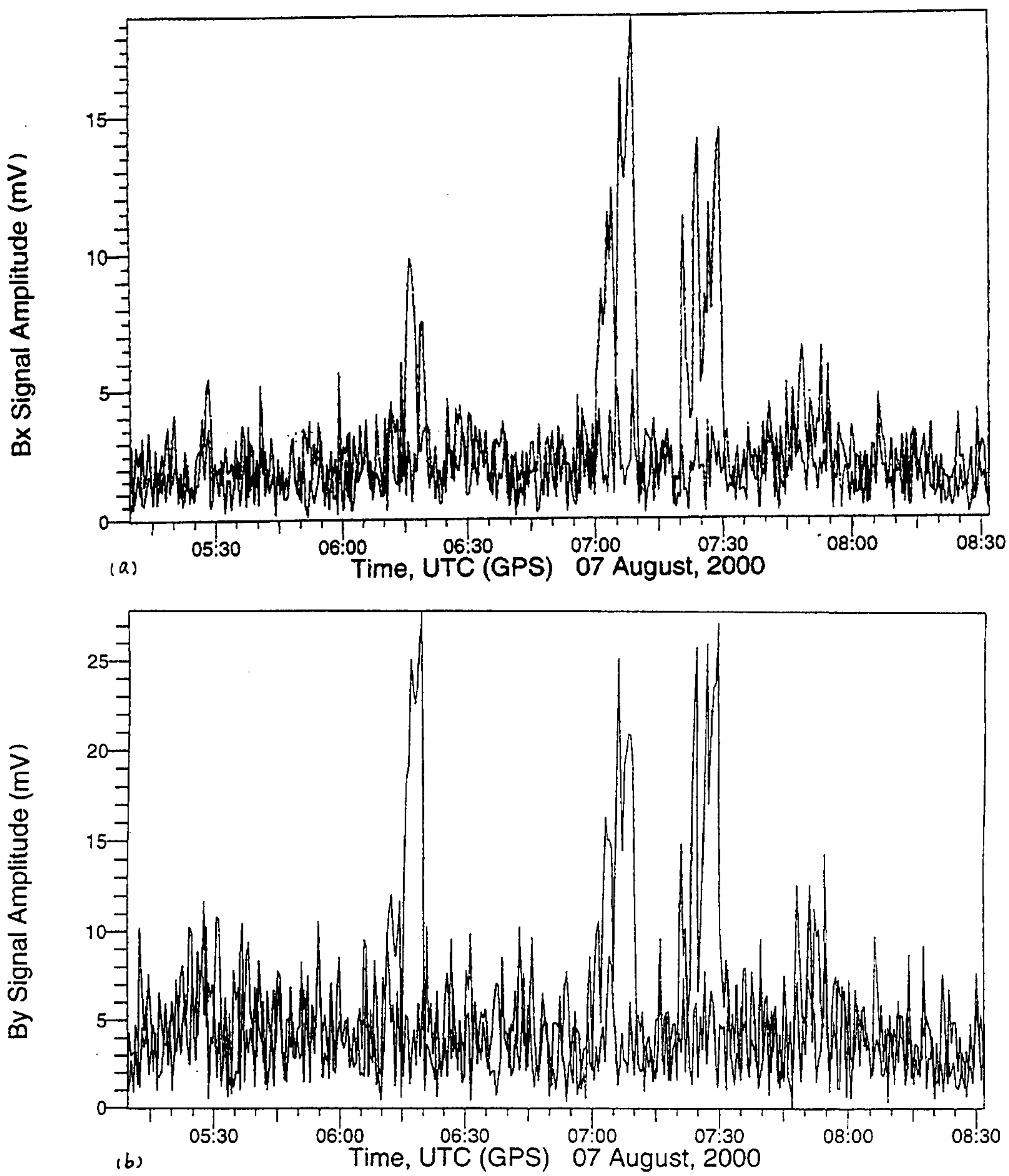

Figure 1. ELF signals at 100 Hz. (a) B_x component and (b) B_y component. The conversion from mV to pT is 1 pT per 75 mV.

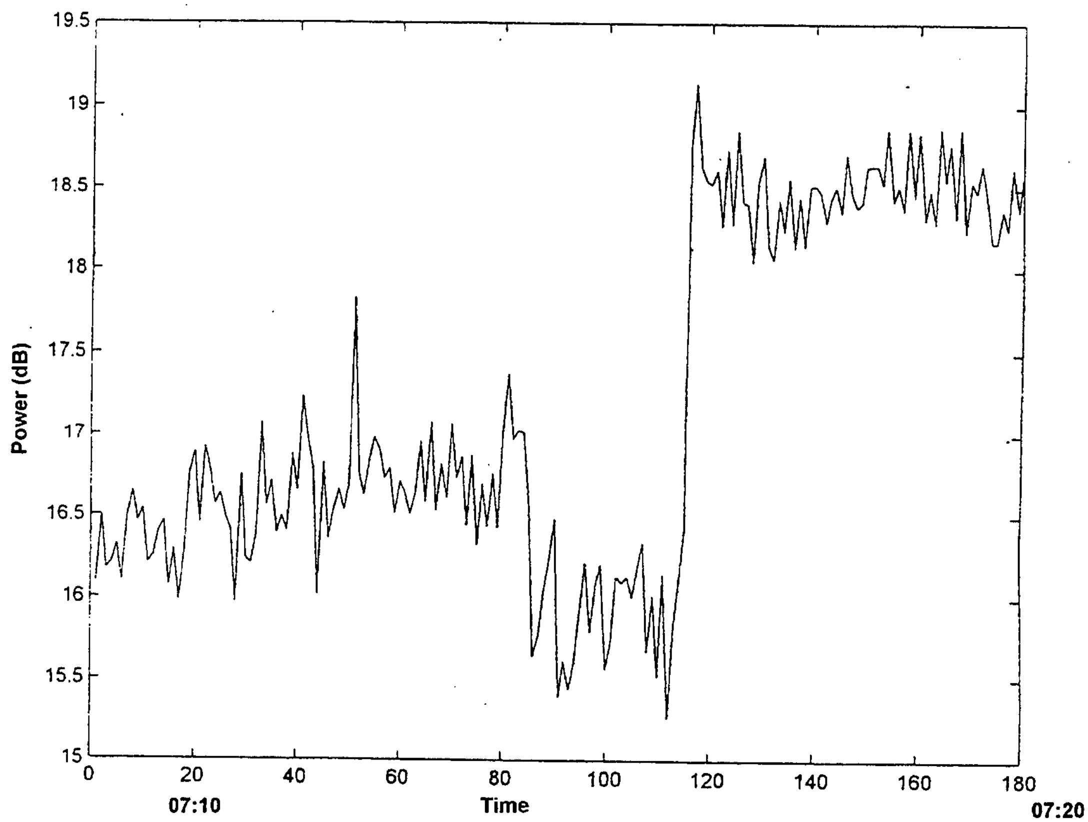

Figure 2. Power of VLF signal at 6.25 kHz

Summary of IRIS for Ionospheric Plasma Heating Experiments at Gakona

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Introduction:

MIT's Ionospheric Radar Integrated System (IRIS) includes (1) a portable radar operating from 10 to 60 MHz, (2) a digital ionosonde, and (3) two VLF receiving systems. The VLF receiving systems were used in our 1997 ionospheric heating experiments at Arecibo, Puerto Rico and Trelew, Argentina [see Lee et al., Geophysical Research Letters, vol. 25, pp. 367-370, and pp. 579-582, 1998, vol. 26, pp. 37-40, 1999; Starks and Lee, Radio Science, vol. 35, pp. 351-360,2000]. It was originally proposed that IRIS be used for HAARP experiments at Gakona in August, after it was tested at Millstone Hill, Massachusetts during June-July.

Two experiments at Gakona, Alaska using IRIS for ionospheric plasma diagnostics were proposed. They include (1) ELF / VLF wave generation via different heater-wave modulation schemes, and (2) generation of ionospheric irregularities and E-region density enhancement. The theoretical background and procedures for the first experiment are described in the proposal entitled "Study of ELF / VLF Wave Generation by Different Heating Wave Modulation Schemes", submitted separately by Spencer P. Kuo and Min-Chang Lee. This experiment was aimed at determining the efficiency of generation schemes and the quality of the generated signals.

Besides the generation of ELF / VLF waves, we planned to investigate the heater-induced ionospheric irregularities and E-region density enhancement, as discussed in Kuo et al. [Geophysical Research Letters, vol. 26, pp. 991-994,1999]. Briefly, kilometer-scale periodic ionospheric density irregularities can be generated by heater waves along the magnetic field in the E region, where the heated ambient NO^+ and O_2^+ ions have reduced electron recombination rates, leading to the enhancement of plasma density . Furthermore, these density irregularities can effectively couple with the heater wave-modulated electrojet to produce a distributed source current for the preferential excitation of whistler waves at frequencies around 25 kHz [Kuo et al., Geophysical Research Letters, vol. 26, pp. 1677-1680, 1999]. Our portable HF / VHF radar and VLF receiving systems, if deployed near the HF heater, will be used to detect the plasma density enhancement and the excited VLF waves, respectively. Our digital ionosonde placed at, for example, the Town of Eagle together with HAARP's digisonde can help monitor the development and evolution of heater-induced kilometer-scale ionospheric density irregularities.

Gakona Experiments and Results:

The federal government issued us frequency licenses to operate the portable radar at Millstone Hill, Massachusetts and at Gakona, Alaska in the past summer. The testing campaign of our radar in Massachusetts was very successful. However, since the summer HAARP experiments were scheduled as demonstrations in the Summer Program 2000, we could only have two hours for the experiments. Thus, we took VLF receiving system, but not the portable radar and digital ionosonde, to Gakona for the experiments. The focused subject was the generation of VLF waves by HF-heater-wave-modulated electrojet. The experiments were carried out by graduate students: Piotr Jastrzebski and Ryan Riddolls and Professor Min-Chang Lee. We collaborated with Professor Spencer Kuo of Polytechnic University for this work.

In our experiments the HF heater transmitted X-mode waves vertically at the frequency of 3.3 MHz. The electrojet was modulated by the heater waves with two schemes: square waves and half-wave rectifier waves at the frequencies of 6.25 kHz, 8 kHz, and 12 kHz, with 4.5 minute on and 0.5 minute off. Our VLF receiving system with two delta antennas was deployed about 7 miles from the HF heater site. Illustrated in Figure 1 show experimental setup including provision for data recording. The procedures for data analysis are briefly described as four steps: (1) 1.0 second of raw data was read into the computer, (2) the data segment was bandpass-filtered around the frequency of interest (*viz.*, 6.25 kHz, 8 kHz, or 12 kHz), (3) the mean of the bandpass filter output was recorded, and (4) these processes were repeated and means were accumulated into a time series.

Presented in Figures 2 and 3 are a photograph of the VLF antenna and a set of analyzed data respectively. In Figure 3, the horizontal axes represent time, while the vertical axes indicate the power flux of recorded VLF signals. The sudden jump of the power flux occurred when we switched the modulation schemes from square waves to half-wave rectified waves. Our very preliminary experiments have corroborated our theory that the efficiency of generating VLF waves depends on the modulation schemes and, indeed, that the half-wave rectified wave modulation is superior to the square wave modulation. In our future experiments we will confirm the theoretical prediction that the signal quality is also dependent upon the wave modulation schemes.

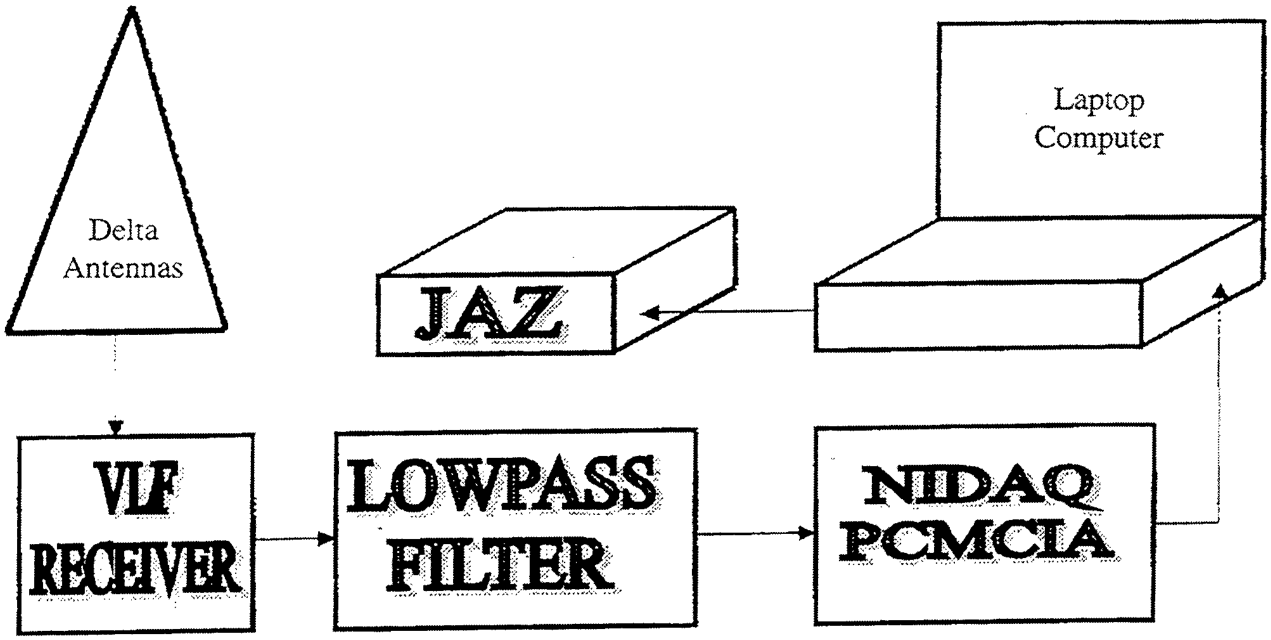

Figure 1. Experiment setup including provision for data recording.

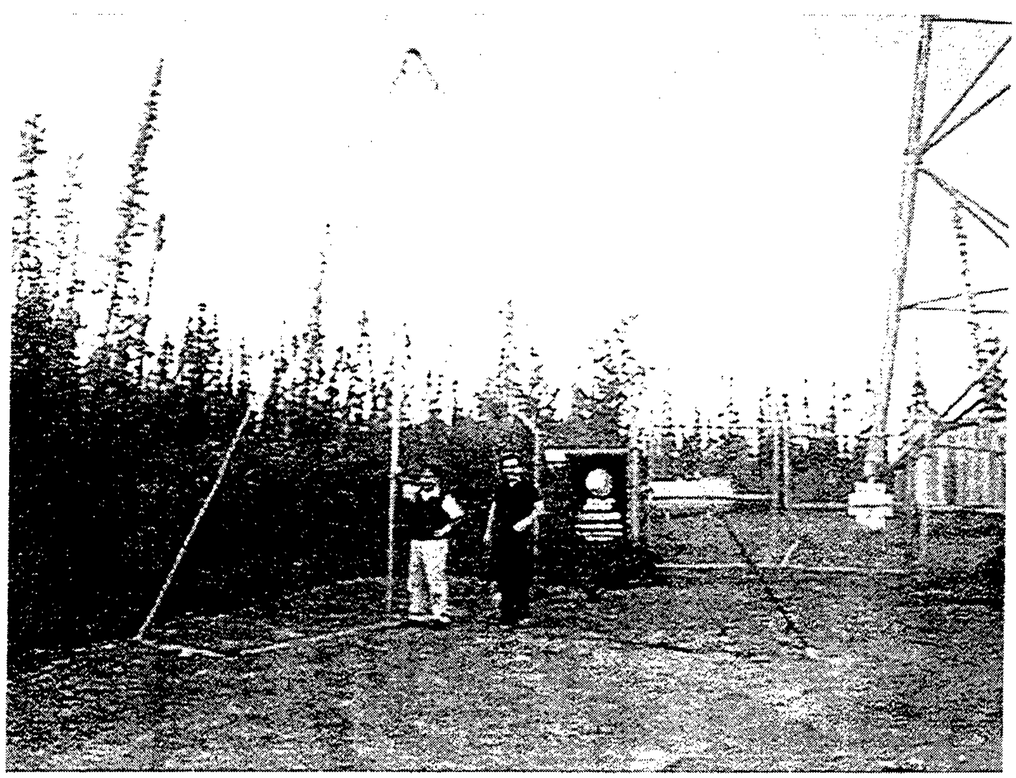

Figure 2. Delta antennas erected at ALASCOM tower site near Gakona Junction, AK.

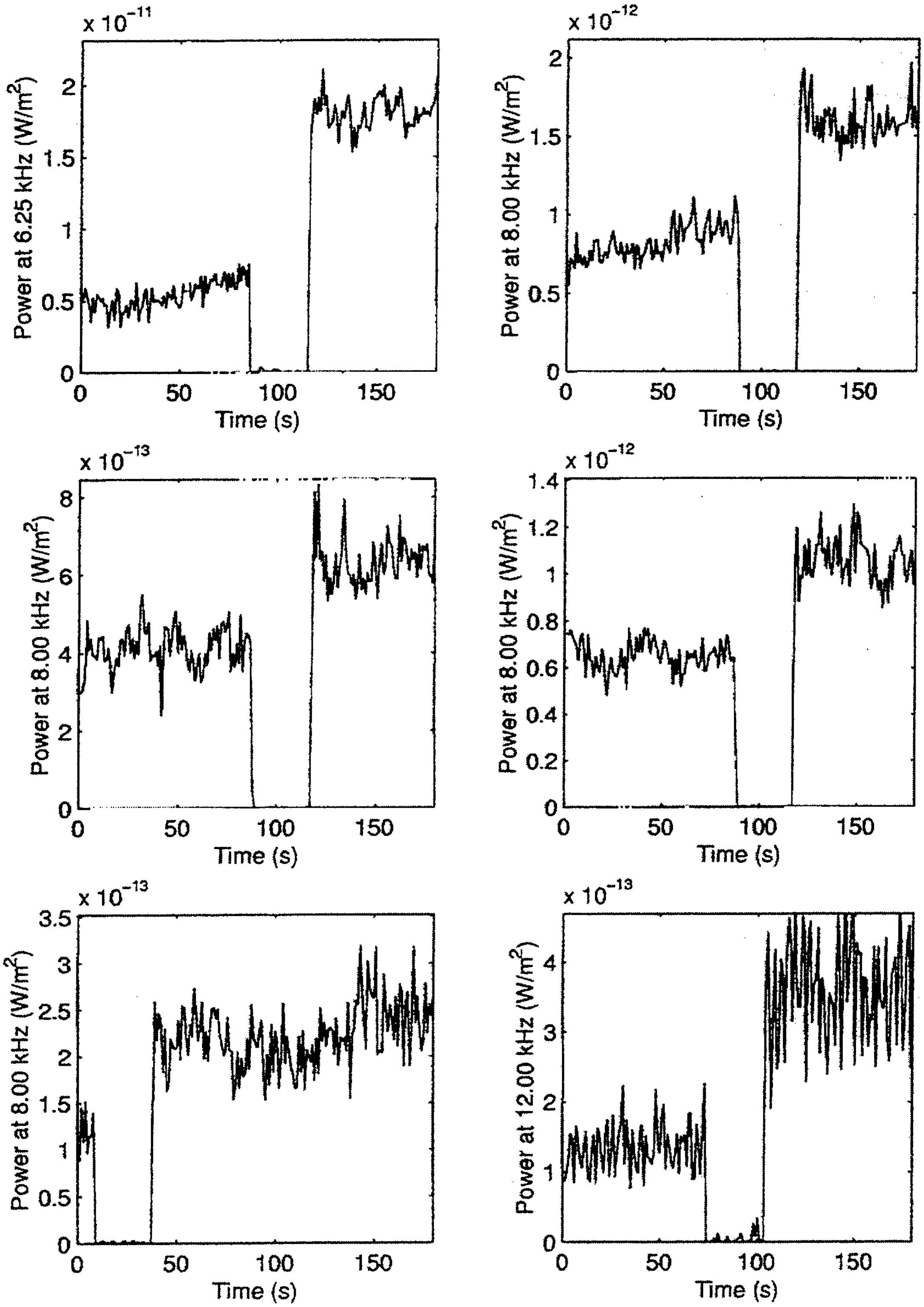

Figure 3. VLF power flux versus time. The jump in power flux occurs when the HAARP transmitter modulation was changed from square to half-wave rectified.

Using the HAARP Heater in an Attempt to Initiate Ion-Cyclotron Waves in the Ionspheric Waveguide

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The Experiment:

Naturally occurring ion-cyclotron waves are excited from above the ionosphere from sources within the magnetosphere, and can propagate within the ionospheric waveguide. On August 8, 2000 we performed an experiment, using the HAARP heater, where the objective was to stimulate the ionospheric waveguide from below such that ion-cyclotron waves propagate in it.

An induction magnetometer is continually operated as part of the University of Alaska Geophysical Institute Magnetometer Array. Analysis of magnetometer data has shown that the ion-cyclotron waves we were trying to duplicate normally occur between 0800 and 2100 local time. Wave frequencies are in the ULF range of 0.1 - 1.2 Hz with a highest occurrence frequency of approximately 0.65 Hz. These physical observations combined with the waveguide hydromagnetic equations derived by Greifinger and Greifinger form the basis for the design of our experiment. Figure 1 presents the induction magnetometer data.

The experiment was set up such that the HAARP heater would irradiate the D-region of the ionosphere with a carrier frequency of 3.3 MHz while modulating the amplitude of the radiation as a sine wave at frequencies in the ULF range of 0.1 - 1.2 Hz.

An interpretation of Greifinger's waveguide equations leads to the idea of heating the D-Region of the ionosphere. This heating, through a coupling of the waveguide modes by the Hall conductivity, may stimulate an ion-cyclotron wave in the F-Region where the waveguide is located.

For the experiment we chose 4 different carrier beam (carrier beam: 3.3 MHz) modulation frequencies: 0.3, 0.5, 0.7, and 0.9 Hz, and we heated in the X-mode at each modulation frequency for 15 minutes. Table 1 is the time log of our experiment.

Time (UTC)	Frequency (Hz)
02:30:00	0.3
02:44:30	**off**
02:45:00	0.5
02:59:30	**off**
03:00:00	0.7
03:14:30	**off**
03:15:00	0.9
03:29:30	**off**

Table 1: Experiment Log

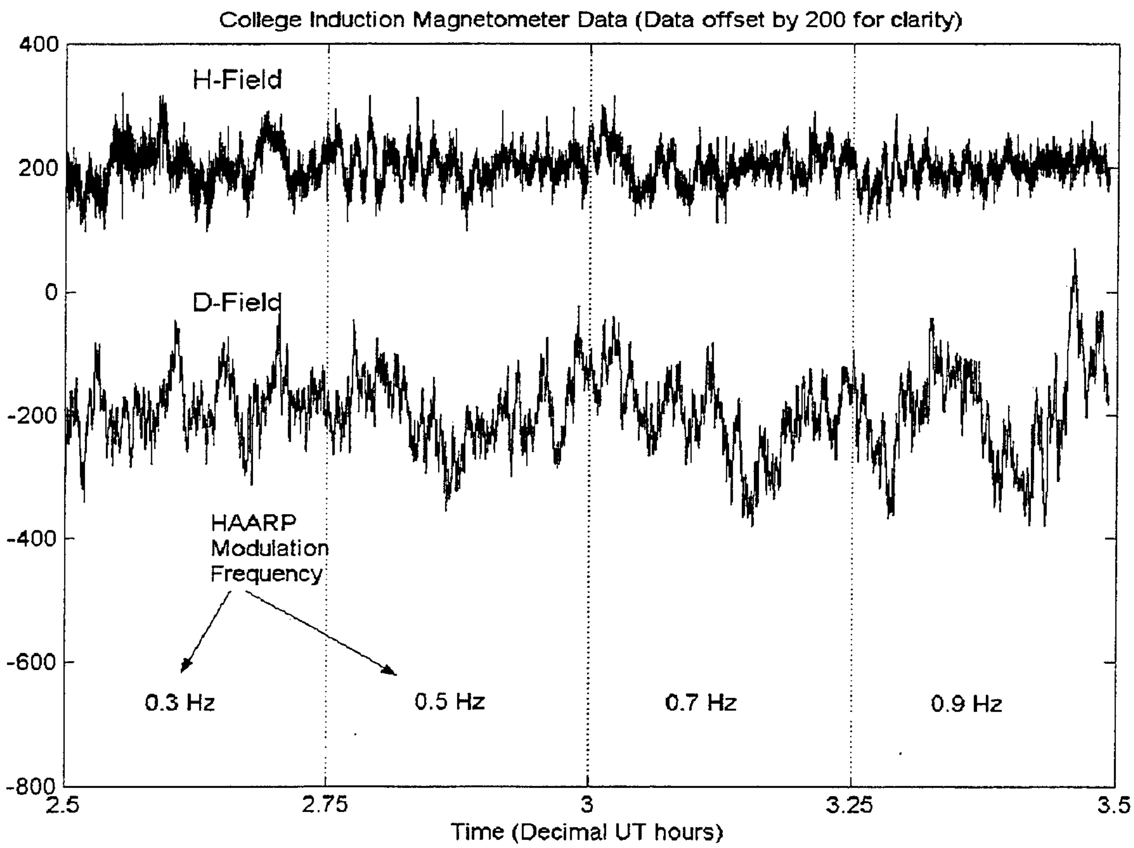

Figure 1. Plot Showing Induction magnetometer data during the 1-hour duration of heating, and equal intervals of 15 minutes for each different modulation frequency.

Data Analysis:

If the experiment was successful, it was assumed the ion-cyclotron wave's oscillating magnetic signature recorded by the induction magnetometer would be very weak. Data from the induction magnetometer at College, Alaska was analyzed in two ways:

First by segmenting the data into equal sections of time that are integer multiples of the period of the modulation frequency, and then stacking/adding the data. Using this technique, background noise in the data will tend to cancel out, but an existing signal with the same period as the modulation frequency will be amplified.

Secondly, by running the data though a Pure State Filter, and then calculating a trace and dipolar spectrogram.

A MATLAB program was written that would divide the data into sections of equal time, so that the time length of each section was an integer multiple of the period of the signal that was assumed to be in the data. Finding the location of the beginning and end of the periods in the data was done using a sine function (having a frequency of the assumed signal) that was a function of the time series stamped on the data. From the output of the sine function you could, more importantly, determine sections of data that were of an equivalent time length, but not necessarily the same number of data points in length.

The located positions of equal time intervals ensured that if there was a signal with the same frequency as the sine function it would be amplified. Note that amplification of the signal would still occur if the signal and sine function were out of phase. The program ran through variations in the number of periods each section of data had in order to test, when looking at the power spectrum of the stacked data, whether a peak at the assumed frequency was an actual signal or noise.

For example, let's look at a piece of data having a length of 15 minutes (900 sec), and you expected to see a signal of 0.3 Hz (1 period = 3.333333 sec) in the data. If you wanted to stack the data such that you have 20 periods of the 0.3 Hz signal, each section would be 66.6666 seconds long (3.3333 x 20 = 66.6666 sec), and would amplify the signal by a factor of 13 (900 / 66.6666 =13.500). No consistent signal was found in the data using this method. The results of using this technique to search for a 0.5 Hz signal are shown in Figure 2.

The second method was more straightforward. It involved running the data through a Pure State Filter followed by the calculation of a trace / dipolar / ellipticity spectrogram. Figure 3 shows the results of this analysis.

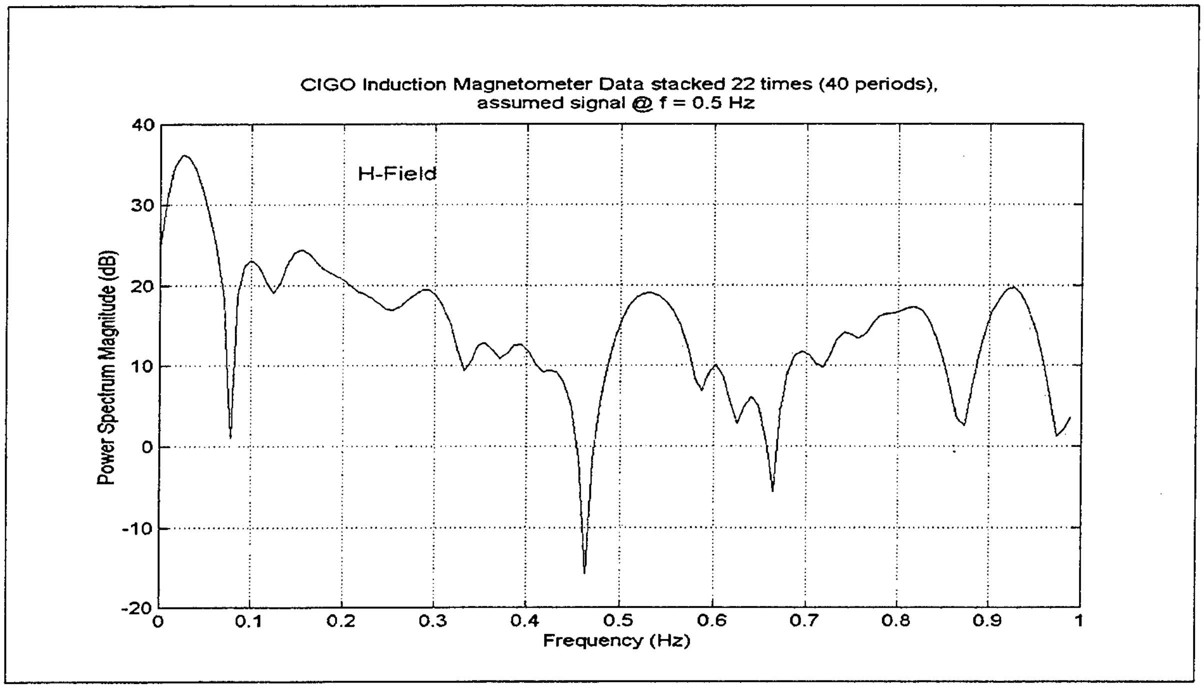

Figure 2. Power spectrum of data assumed to have a 0.5 Hz signal. The data was broken into sections having each 40 periods, and then stacked giving a possible amplification factor of 22. Note that the peak that occurs at 0.53 Hz is not consistent with other stacking multiples of the same data.

Summary & Conclusions:

Although the electrical current flow due to HAARP heating D-Region is not well understood it was assumed for this experiment that the current distribution could be characterized mainly as a magnetic dipole. The dipole, in theory, would oscillate the bottom of the waveguide and stimulate the propagation of ion-cyclotron waves. However, no signals were detected at the anticipated frequencies.

Power Spectral analysis of the College induction magnetometer data during the 1 hour of heating gives a minimum detected field variation of about 0.5 pico Tesla (*cf.* Table 2). From this we can calculate that if a vertically directed magnetic dipole was created, from the heating of the D-Region by HAARP, it would have a magnetic dipole moment less than 10^{12} T·m^3. If ion-cylcotron waves did propagate down the waveguide the total detectable Pedersen current that escaped the waveguide would be less than 1 Amp. Since the current distribution due to heating is not well known, we need to take a closer look at what kind of interaction we want to create in the D-Region in order to make this experiment a success.

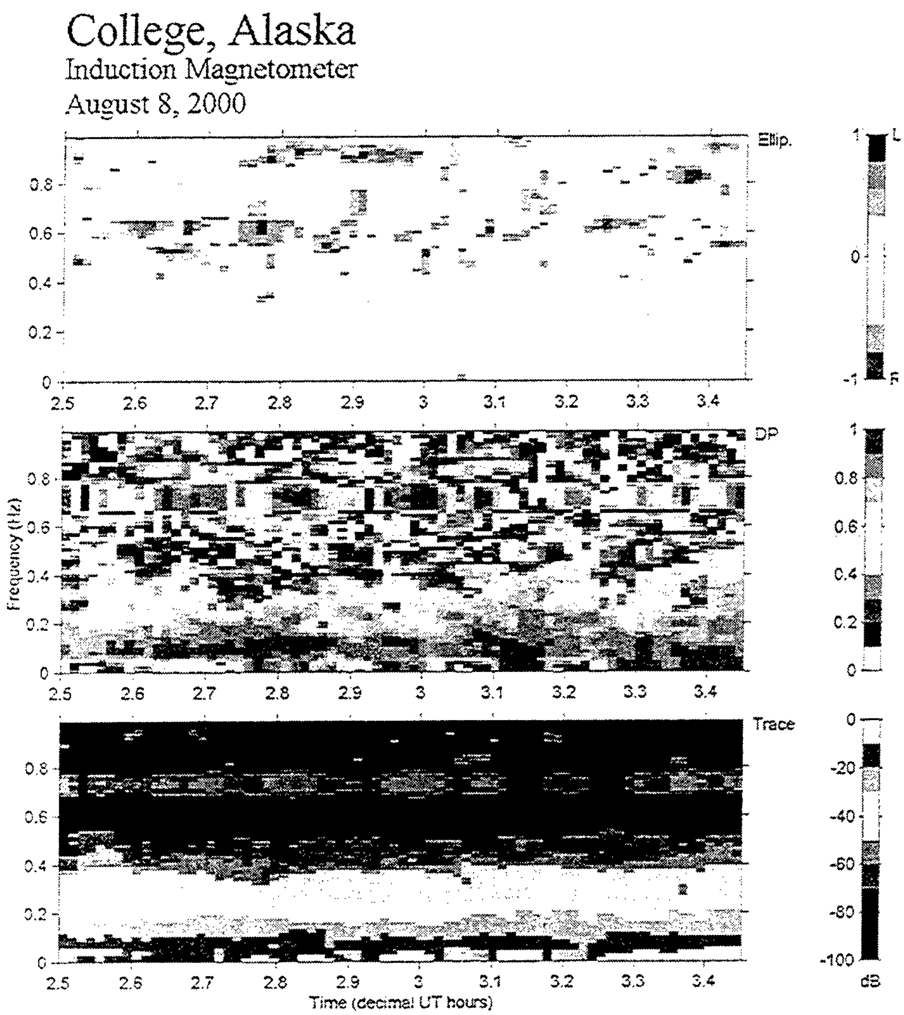

Figure 3. Spectrogram of filtered Data using Pure State Filter showing Trace / Dipolarization / Ellipticity. No evidence of a signal at the modulated frequency can be seen in the trace. It should be noted that the data from the Kaktovik Induction magnetometer also shows no evidence of a signal.

f (Hz)	B(pT)
0.3	1.0 ± 0.6
0.5	0.5 ± 0.3
0.7	0.33 ± 0.04
0.9	0.23 ± 0.01

Table 2. Minimum magnetic field variation detected during heating

SEE and Radar Observations of HAARP Interaction Experiments

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Executive Summary

Scientific Objective:

Previous experiments performed at Arecibo Observatory and at EISCAT in Tromsø, Norway, demonstrate a significant, reproducible temporal and spatial structuring of the plasma line signal in incoherent scatter radar (ISR) measurements made during HF interaction experiments in the F-region of the ionosphere. We performed measurements of the response of a (SuperDARN) radar-scattered "ion line", and stimulated electromagnetic emissions (SEE) during F-region interaction experiments including pulse modulation of the HAARP HF radiowaves.

Observation Technique:

The HAARP HF transmitter was operated in O-mode at full power ($P_{xtr} =$ 920 kW), vertical incidence, at frequencies (4.55 to 5.90 MHz) chosen for optimal deposition of RF power in the F-region of the ionosphere. A variety of HF pulsing schemes were used including HF pulse widths of 100 ms down to 25 ms. The HAARP duty cycle was varied from CW down to 33%. SEE spectra were recorded using the AFRL receiver. The SuperDARN Kodiak station radar was operated to record scatter from HF induced irregularities over HAARP.

Preliminary Results:

Operating in CW mode, the HF pump reliably induced a strong, distinct "downshifted maximum" (DM) feature in the stimulated electromagnetic emission (SEE) spectra associated with the development of irregularities. Operating in pulsed mode, a decrease of the pulse width to 50 ms with 50% duty cycle relaxed the DM feature while maintaining the continuum part of the SEE spectra. The narrow continuum (NC) and broad continuum (BC), as variously defined, overlap in the frequency regime of the DM feature. Both the NC and BC are quite prominent in the data, as can be seen on the display to the right in Figure 1, while the DM is absent. The NC was maintained using HF pulse widths down to 25 ms with a 50% duty cycle. For the first time, the Kodiak radar was able to record induced scatter over HAARP while operating the heater in pulsed mode (see figure). It is significant for interpretation that the Kodiak radar was able to detect induced scatter in the absence of the DM, with only the continuum present. Increasing the HF pulse width to 100 ms (50% duty cycle) pumped up the DM.

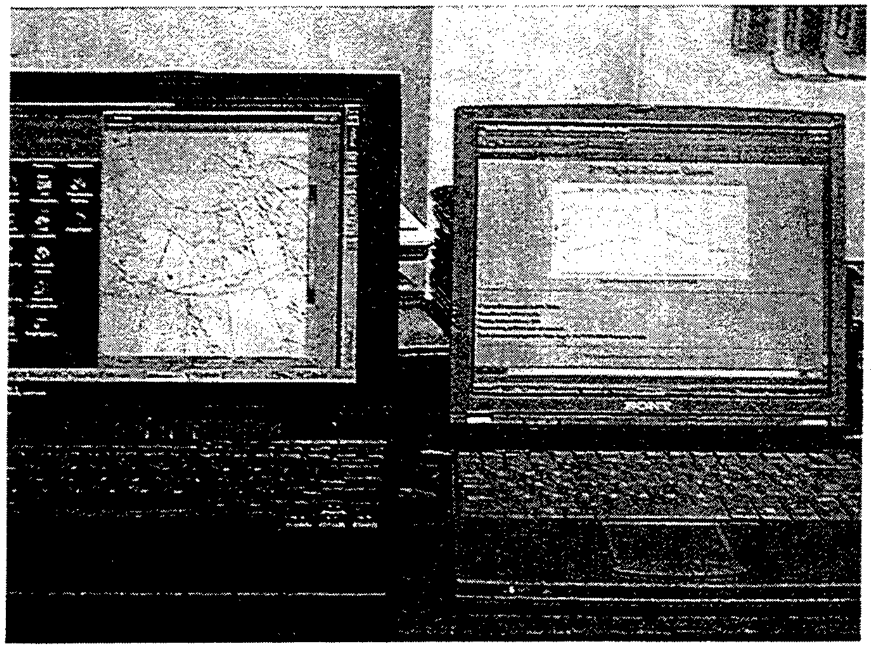

Figure 1. Simultaneous occurrence of HF (SuperDARN) radar (left) and SEE (right) features. The SuperDARN display shows returns over HAARP, while the SEE display shows the narrow continuum (NC) during pulsed mode (note absence of the DM). The HF pulse width was 25 ms with a duty cycle of 50%.

Background Physics:

Radar scatter studies of the so-called 'plasma line' (PL) recorded during HF interaction experiments performed in the F-region of the ionosphere, have long demonstrated a complex, but <u>reproducible</u>, temporal and spatial structuring [Muldrew and Showen, 1977; Showen and Kim, 1978; and Duncan and Sheerin, 1985]. A typical record of the time history of the PL recorded at Arecibo by Duncan and Sheerin (1985), shows an 'early' (a few milliseconds) return enhancement in the PL followed by a much stronger peak in the PL occurring tens of milliseconds later. This strong peaking of the PL return is labeled the "overshoot" effect and has been studied in experiments at Arecibo (Sheerin, 1986) and at Tromsø (Stubbe, 1996). The weaker, prompt enhancement in the plasma line was correspondingly christened the "mini-overshoot". These temporal features were correlated with altitude signatures studied by Duncan and Sheerin

(1985) and later by Djuth, et al., (1994), and Sulzer,et al., (2000). These studies indicate that different plasma line features may be detected at different altitudes. Cole and Kennedy (1999) have recently reported results from VHF scattering from field-aligned irregularities (FAI) stimulated by the HAARP HF radiowave. It is interesting to note the temporal features in these scattering experiments. It is also important to note observations of overshoot effects in SEE spectra (Bernhardt and Selcher, private communication, 1998). The overshoot effects are dependent on the HF pulse length and duty cycle (fraction of time the HF transmitter is on). This provided an obvious starting point for the first-ever attempts at recording these effects at HAARP.

The DM feature in SEE spectra is associated with the development of field-aligned irregularities (FAI). The NC is associated with small-scale turbulence such as Strong Langmuir Turbulence (SLT). As such, it is of interest to study the NC in the absence of the DM. This protocol is analogous to the study of the prompt PL radar returns in cold start, low duty cycle experiments (e.g. at Arecibo) designed to study SLT in absence of FAI.

Results:

Two approximately two-hour runs were performed on 6 and 7 August 2000. Data from each of these runs is currently being analyzed. A sample experiment log from the first two-hour run is reproduced here.

Operating in CW mode, the HF pump reliably induced a strong, distinct "downshifted maximum" (DM) feature in the SEE spectra associated with the development of irregularities. Operating in pulsed mode, a decrease of the pulse width to 50 ms with 50% duty cycle relaxed the DM feature while maintaining the continuum part of the SEE spectra. The narrow continuum (NC) and broad continuum (BC), as variously defined, overlap in the frequency regime of the DM feature. Both the NC and BC are quite prominent in the data, as can be seen on the display to the right in Figure 1, while the DM is absent. The NC was maintained using HF pulse widths down to 25 ms with a 50% duty cycle (Figure 2). For the first time, the Kodiak radar was able to record induced scatter over HAARP while operating the heater in pulsed mode (*c.f.* Figure 1). It is significant for interpretation that the Kodiak radar was able to detect induced scatter in the absence of the DM, with only the continuum present. Increasing the HF pulse width to 100 ms (50% duty cycle) pumped up the DM.

Experiments Log (Sample)
"SEE and Radar with Pulsed HF"
6-7Aug 2000

Sheerin (PI) and Mills (Student)
Groves (SEE receiver)
Bristow (SuperDARN)

HF Xmtr: O-mode, Vertical, P_t = 92x10kW= 920 kW

Local Time (ADT) (UT – 8 hrs)	UT (ADT + 8 hrs)	Xmtr Freq. (MHz)	HF Xmtr Mode	Comments
16:05 6 Aug 00	00:05 7 Aug 00		OFF	End of Bristow Expt
16:12:30	00:12:30	4.55	CW	Riometer showing
16:30:40	00:30:40		OFF	strong absorption
16:32:12	00:32:12	4.55	CW	
16:40:00	00:40:00		OFF	
16:50:00	00:50:00	4.89	CW	Strong DM in SEE
17:01:00	01:01:00		OFF	
17:02:00	01:02:00	4.89	50 ms ON/50 ms OFF	DM disappears
17:21:30	01:21:30		OFF	
17:22:00	01:22:00	4.89	CW	
17:34:00	01:34:00		OFF	
17:39:00	01:39:00	4.89	100 ms ON/100 ms OFF	First radar detection of HAARP pulsing DM returns in SEE
17:50:09	01:50:09		OFF	
17:56:00	01:56:00	4.89	25 ms ON/25 ms OFF	NC/BC developed in SEE without DM
18:06:00	02:06:00		OFF	
18:10:00	02:10:00	4.89	25 ms ON/25 ms OFF	SDARN radar detects HAARP/DM absent
18:15:00	02:15:00		OFF	END

The observing techniques for the second run (7 Aug. 2000) are synopsized as follows:

Schedule for Pulsed Experiments
7 Aug. 2000
22:20 - 24:00 UT

Pointing	Zenith
Power	920 kW
Frequencies (MHz)	5.90, 4.90
CW	
Pulse sequence 1	100 ms ON/100 ms OFF (50% duty cycle)
Pulse sequence 2	75 ms ON/75 ms OFF
Pulse sequence 3	50 ms ON/50 ms OFF
Pulse sequence 4	25 ms ON/25 ms OFF
OFF	
Pulse sequence 5	100 ms ON/200 ms OFF (33% duty cycle)
Pulse sequence 6	75 ms ON/150 ms OFF
Pulse sequence 7	50 ms ON/100 ms OFF
Pulse sequence 8	25 ms ON/50 ms OFF
Repeat at new Frequency	

Discussion:

In this brief campaign, we were able to observed three significant effects pursuant to our scientific objective.

a. After demonstrating production of the DM feature in the SEE spectra taken at HAARP, we were able to suppress this feature using a shorter HF pulsewidth. The DM is associated with FAI. The suppression of the DM may allow for the study of the NC and BC features. The DM was produced with 50% duty cycle of at least 100 ms HF pulsewidths.

b. Another significant result was the first detections of "ion line" scatter in the Kodiak (SuperDARN) radar returns with HAARP operated in pulsed mode. The radar was able to detect scatter over HAARP down to the shortest heater pulsewidths used (25 ms). This technique holds great potential for diagnosing HAARP experiments.

c. By using shorter heater pulsewidths, we were able to study the evolution of the NC in absence of the DM feature. The connection of the NC feature with small-scale turbulence can then be studied and this data analysis has begun. The development of small-scale turbulence (e.g. SLT) may be an important factor in the use of HAARP.

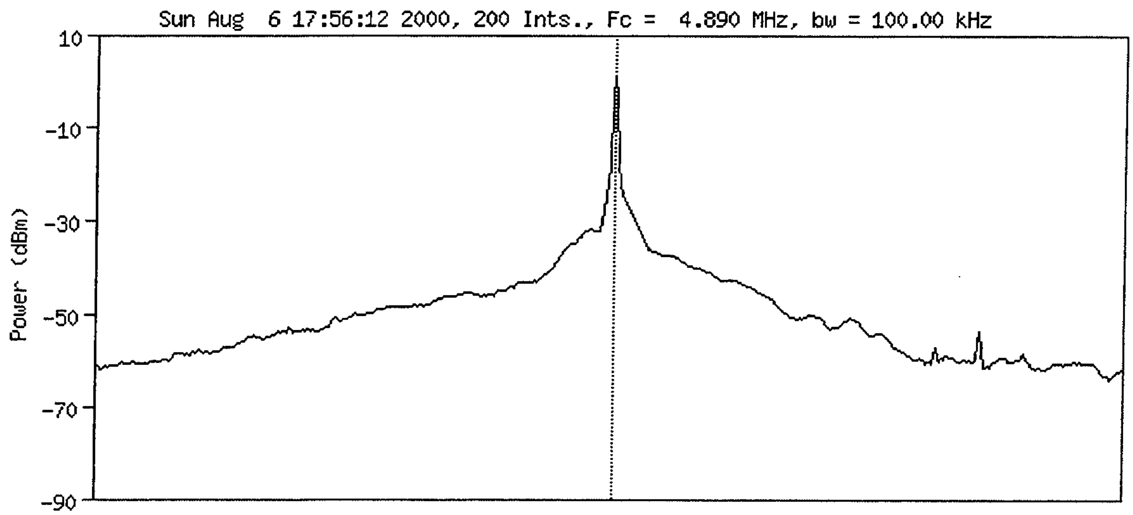

Figure 2. SEE spectra showing NC feature with DM absent. HF pulse width 25 ms with 50% duty cycle.

Conclusions:

We have made some of the first SEE and radar measurements of pulsed HAARP interaction experiments. The use of short heater pulsewidths was shown to suppress the DM feature in SEE spectra, allowing the study of small-scale turbulence through its associated NC feature. The Kodiak SuperDARN radar was demonstrated to provide a useful diagnostic of induced scatter in the heated region during pulsed HAARP operation and in the absence of the DM feature in the SEE. Utilization of these techniques will permit the study of important phenomena (e.g. SLT) as it occurs in ionospheric interaction experiments.

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Acknowledgements

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